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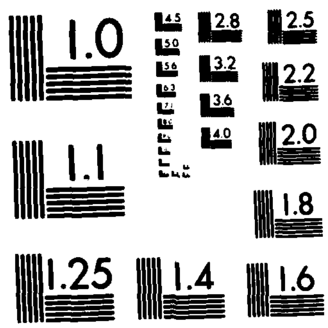

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Prepared for

ST PAUL DISTRICT

U.S. ARMY CORPS OF ENGINEERS

CONTRACT NO.

DACW37-81-C-0027

AD-A146 708

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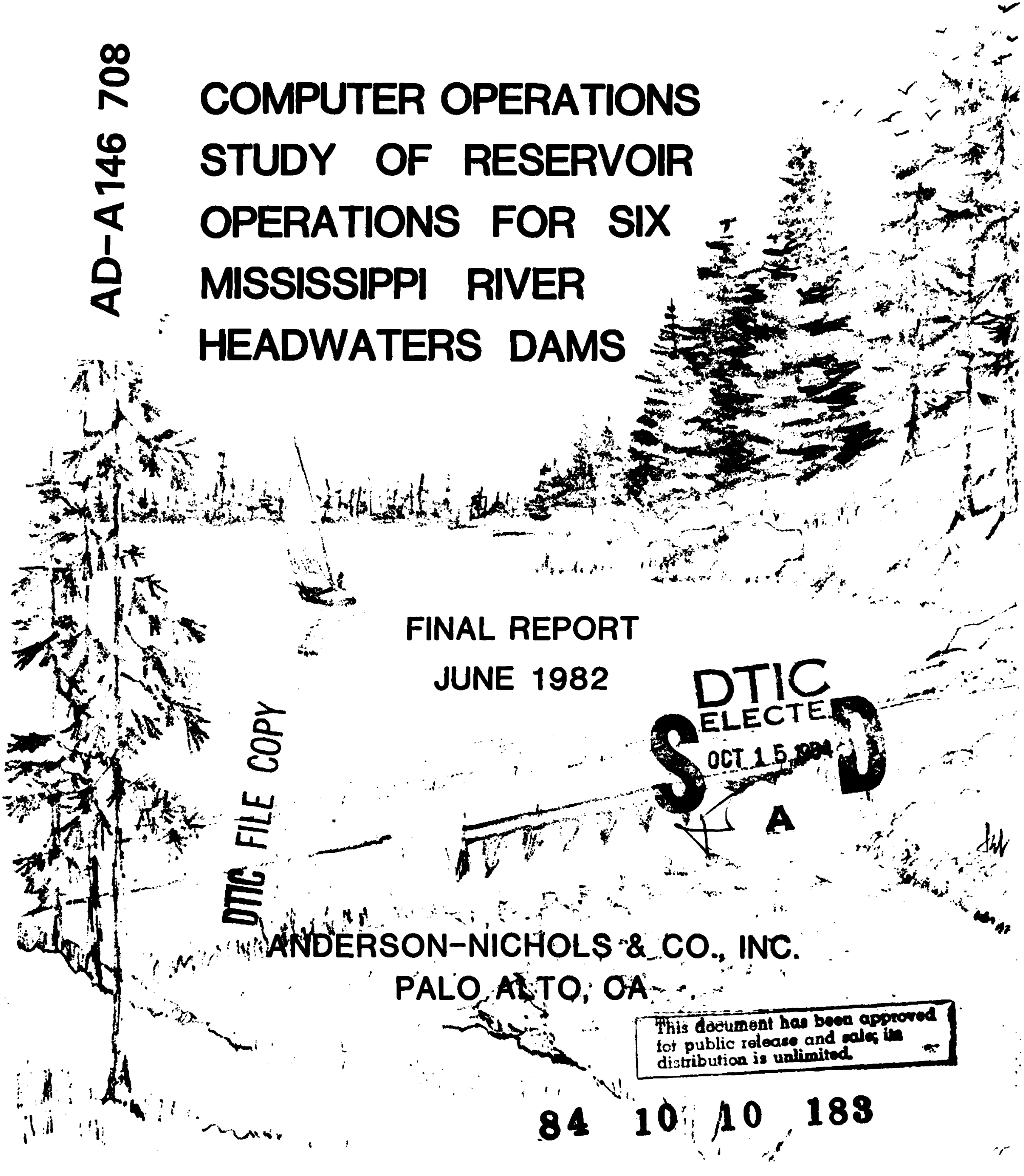

FINAL REPORT

JUNE 1982

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PALO ALTO, CA

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RESERVOIRS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The study used the HEC-5 computer program, "Reservoir System Operation for Flood Control and Conservation," to evaluate the operation plans for the six headwater reservoirs, Winnibigoshish, Leech, Pokegama, Sandy, Pine and Gull, on the Mississippi River in northern Minnesota. Reservoir operation rules are established for each plan based upon the desired plan objective. Ten operation plans are evaluated.

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SUMMARY

The study uses the HEC-5 computer program, "Reservoir System Operation for Flood Control and Conservation," to evaluate the operation plans for the six headwater reservoirs on the Mississippi River in northern Minnesota. Reservoir operation rules are established for each plan based upon the desired plan objective. Computer simulation results for the remaining nine plans are compared to Plan 1 to define expected changes in hydraulic, frequency, and economic effects at key locations. The ten reservoir operation plans are:

Plan 1 -	Present Operating Plan
Plan 2 -	Low Flow Plan, 1600 cfs Minimum Flow at Anoka
Plan 3 -	High Flow Plan, Increased Flood Protection at Aitkin
Plan 4 -	Natural Flow Plan, Pre-reservoir Conditions
Plan 5 -	Low Flow Plan, 2275 cfs Minimum Flow at Anoka
Plan 6 -	Low Flow Plan, 4800 cfs Minimum Flow at Anoka
Plan 7 -	Hydropower Plan
Plan 8 -	Minimize Lake Property Damage Plan
Plan 9 -	Conservation Plan
Plan 10-	Sandy Lake Plan

Economic benefits are computed for reduction of high and low water damages at the six reservoirs (during the summer recreation season, May through September), flood protection at Aitkin, and water supply for the Minneapolis/St. Paul metropolitan area. The 47-year simulation period (1930-1976) for each plan shows the relative effect of competing objectives.

Plan 1 with a total average annual damage (AAD) of $600,000 at the reservoirs and Aitkin (see accompanying summary table) is the base condition with which the other plans can be compared. Plan 3 is the best plan for reducing AAD at Aitkin ($60,000 reduction); however, the net increase at the reservoirs ($270,000) brings the total AAD to $810,000 - a substantial increase over Plan 1. Plan 8 best minimizes lake property damage with a reduction of $100,000 AAD. This is offset by a $140,000 AAD increase at Aitkin. Plan 9 provides improved conditions for growing wild rice at Leech and walleye spawing at Winnibigoshish. Although no

economic benefits are computed for these activities, it is interesting to note that the AAD is not adversely affected by this plan. In fact, there is a slight AAD decrease of $30,000 compared to Plan 1.

In terms of water supply benefits (Plans 2, 5, and 6) the total benefit is substantial, close to $13 million for Plan 6. These benefits are based on a relative net worth of water at Anoka of $385 per cfs-day up to the minimum flow target. Plan 6 has the highest net benefit due to its high target of 4800 cfs. However, as is shown in the accompanying table the total AAD at the reservoirs and Aitkin increases as the minimum flow target increases. When comparing the combination of AAD reduction and water supply benefits, the three plans specifically targeted for water supply provide substantially higher benefits than the other plans. This is due to the high value of the water supplied to Anoka in comparison to the total damages at the reservoirs and Aitkin.

Plan 7 (Hydropower) and Plan 10 (Sandy Lake) were not studied using HEC-5. A brief discussion of these two plans is found in Section 10 and 13, respectively.

A number of major HEC-5 improvements and program modifications were made by HEC during the course of the study to enhance the use of the model for this study. All program deficiencies were corrected prior to the final computer analysis of the plans except for one, which affects the results of Plan 2, 5, and 6. The effect of this problem is discussed in sections presenting the results of these three plans.

Complete summaries of the analyses of the results for each plan studied using HEC-5 are presented in the Appendix, bound separately. A description of the support programs used with HEC-5 also can be found in the Appendix. All the computer results are on magnetic tape supplied to the St. Paul District.

ECONOMIC RESULTS SUMMARY TABLE
($1,000)

	Average Annual Damage			Net Change (Increase) in AAD*	Average Annual Net Benefit (Cost) at Anoka*	Total Benefit (Cost)*
	6 Reservoirs	Aitkin	Total			
1 - Present Operating Plan	320	280	600	-	-	-
2 - Low Flow (1600 cfs)**	330	280	610	(10)	2560	2550
3 - High Flow	590	220	810	(210)	(520)	(730)
4 - Natural Flow	1710	470	2180	(1580)	(2650)	(4230)
5 - Low Flow (2275 cfs)**	420	280	700	(100)	6030	5930
6 - Low Flow (4800 cfs)**	460	280	740	(140)	12850	12710
8 - Minimize Lake Property Damage	220	420	640	(40)	(50)	(90)
9 - Conservation	290	280	570	30	230	260

*Relative to Plan 1
**Results include effects of HEC-5 problem (see appropriate sections for plan details)

ACKNOWLEDGEMENTS

This study was performed by the Resource Technology Division of Anderson-Nichols under contract number DACW37-81-C-0027 with the St. Paul District of the U.S. Army Corps of Engineers. Mr. Carl Stephan served as Study Manager for the District and provided coordination, data, and assistance throughout the project. Mr. Mark Ziemer was a principal technical contact with the District and provided guidance and review of technical issues. Anderson-Nichols staff that contributed to this study include: Mr. Doug Beyerlein (Project Manager), Dr. Anthony Slocum (Principal Investigator), Dr. Benjamin Roberts, Ms. Kathy Lahanas, and Mr. John Imhoff.

Mr. Bill Eichert and the staff of the Hydrologic Engineering Center, Corps of Engineers, developed and adapted HEC computer programs (HEC-5, DSS, FATSO, PLOT, and EAD) for use in this study. They provided invaluable assistance in running these programs, analyzing computer output, and evaluating model performance. In addition, the HEC computer system was used for all data formulation and computer runs. The timely and effective participation of HEC was a key ingredient in the performance of this project. Particular people at HEC who provided assistance include Mr. Harold Kubik, Ms. Penni Baker, Mr. Bill Charley, Mr. Brent Cullimore, Mr. Lowell Glenn, Ms. Marilyn Hurst, and Dr. Art Pabst.

SECTION 1

BACKGROUND

This study has been performed by Anderson-Nichols & Co., Inc. under contract to the U.S. Army Corps of Engineers, St. Paul District; Contract Number DACW37-81-C-0027. The study results are to be used to assist the Corps in preparing a Stage III Feasibility Report for the Mississippi River Headwaters Lakes Study.

SCOPE OF WORK

The contract Scope of Work is included in Appendix A. Briefly, the work effort under this contract is directed towards reevaluating the effects of four reservoir operating plans already developed in a previous contract and six additional operating plans for the six Mississippi River Headwaters Dams - Winnibigoshish, Leech, Pokegama, Sandy, Pine, and Gull. The previous work which was accomplished by the St. Anthony Falls Hydraulic Laboratory, University of Minnesota (SAFHL), utilized an early version of the Hydrologic Engineering Center's (HEC) HEC-5c Computer Program.

This work is based upon the current version of HEC-5, a new statistical program for time series data frequency analysis, and the HEC Expected Annual Flood Damage Program. The computer results provide the hydraulic and economic effects of implementing each of the evaluated plans.

The four reevaluated plans are:

- Plan 1 - Present Operating Plan
- Plan 2 - Low Flow Plan, 1,600 cfs at Anoka
- Plan 3 - High Flow Plan
- Plan 4 - Natural Flow Plan

The six new plans are:

- Plan 5 - Low Flow Plan - 2,275 cfs at Anoka
- Plan 6 - Low Flow Plan - 4,800 cfs at Anoka
- Plan 7 - Hydropower Plan
- Plan 8 - Minimize Lake Property Damage Plan
- Plan 9 - Conservation Plan
- Plan 10 - Sandy Lake Plan

In addition, a sensitivity analysis was performed on the reservoir elevation - area - capacity relationships to test the impact of potential inaccuracy on expected results for the evaluated operating plans.

MISSISSIPPI RIVER HEADWATERS AREA

The Mississippi River Headwaters Area lies in the State of Minnesota. Beginning at Lake Itaska in Northwest Minnesota, the river flows through relatively flat terrain for a headwaters region with numerous lakes and low wetlands. The U.S. Army Corps of Engineers constructed dams on six of these lakes during the period 1881 to 1913. They were initially constructed for navigation and logging; however, over the years competing uses such as flood reduction and recreation have been incorporated into the reservoir operation plans. This study evaluates the effect of alternative plans on the controlled lakes as well as selected stream locations down to St. Paul, Minnesota.

The total drainage basin above St. Paul is 19,400 square miles (does not include Minnesota River Basin). A general location map of the area is shown in Figure 1-1. General operating data for the six Mississippi River Headwaters Reservoirs is shown in Figure 1-2 and Figure 1-3.

PREVIOUS WORK

The most recent work was performed by the St. Anthony Falls Hydraulic Laboratory under contract to the St. Paul District Corps of Engineers. Their report, "The Effects of Different Operating Plans for the Six Mississippi River Headwaters Dams," dated August 1979 (see Reference 1) provides much of the base data used for this study. The results of this work was incorporated into the St. Paul District Corps of Engineers "Stage 2 Summary Report, Mississippi River Headwaters Lakes Study" (Reference 2).

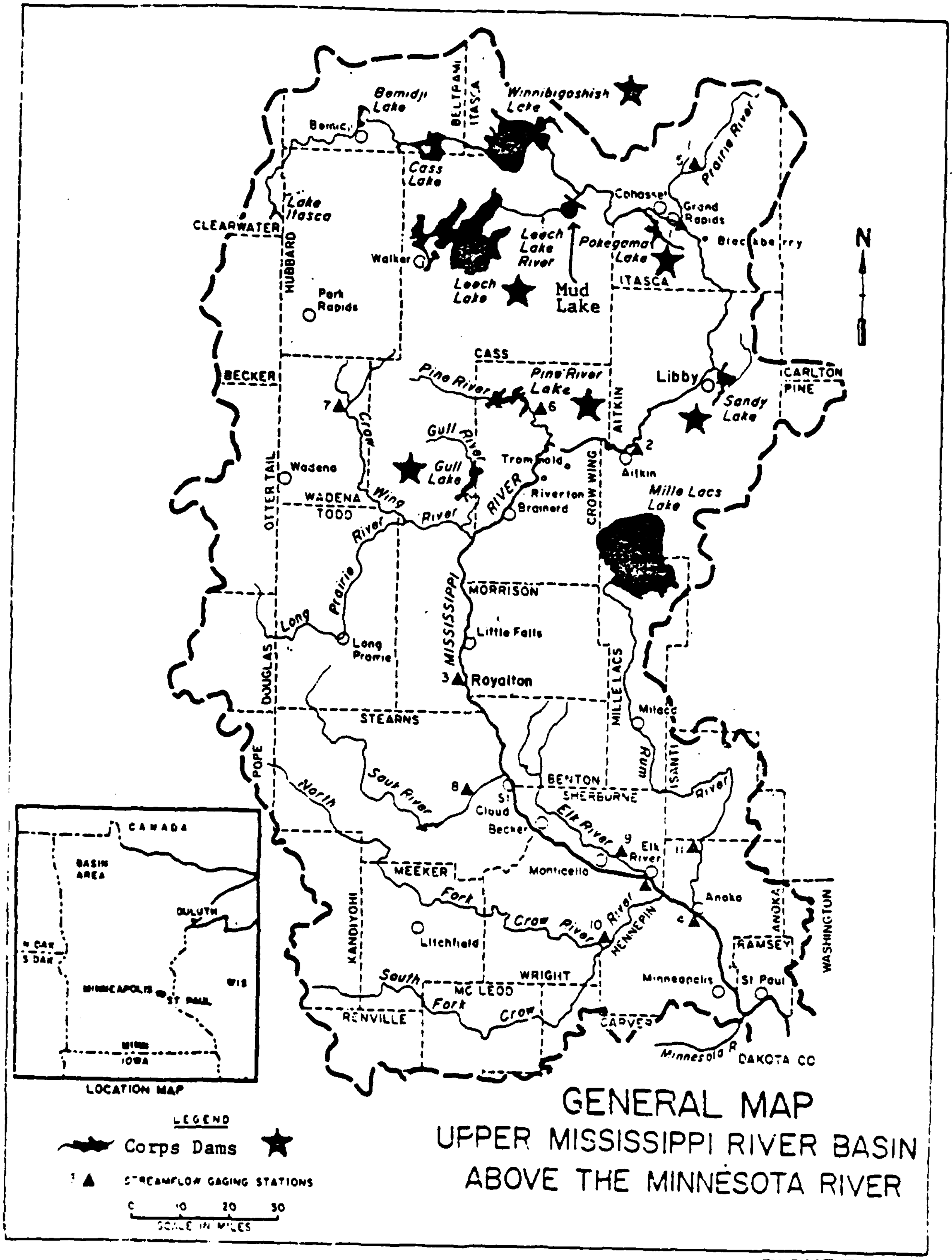
Studies and reports concerning the Headwaters Area date back to the 1870's. The Corps Stage 2 Summary Report provides a good summary of recent work on pages 6-10 (Reference 2).

HEC-5 PROBLEMS

The previous study conducted by the St. Anthony Falls Hydraulic Laboratory found a number of problems (Reference 1; Appendices H, L, M, P)

when trying to use and modify the newly released (1979) HEC-5 computer program on their computer system. The SAFHL study experienced a number of problems that were never completely resolved. SAFHL completed their report but never had a complete, working version of HEC-5. Thus, prior to our attempt to use HEC-5, the most recent version of the program was revised by the Hydrologic Engineering Center (HEC) in Davis, California, to ensure that the reservoir operation logic was performing properly. This revision of the program was completed in the autumn of 1981 by HEC and by the end of the year a number of plans had been analyzed using the results produced by HEC-5.

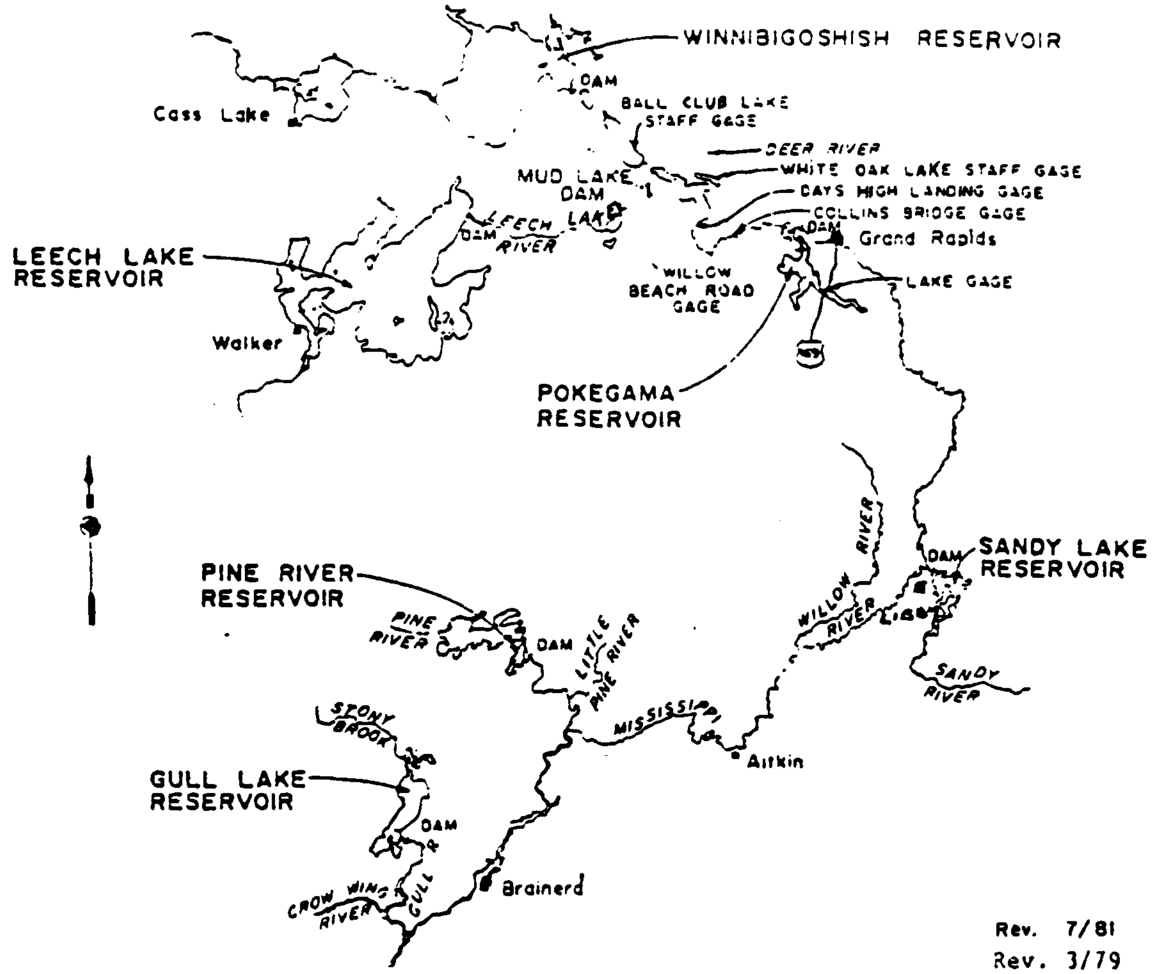
A review of the HEC-5 results in January 1982 revealed some cases where the program was incorrectly operating the tandem reservoirs (Winnibigoshish and Leech) at the upstream end of the watershed. The identification of this problem (and later others) in the HEC-5 program started an iterative process of HEC-5 output review, problem identification, correction of the problem by HEC, and the rerunning of plans. Each problem was corrected by HEC and all corrections were made prior to the final computer runs of the study plans, except for the last problem discovered. This problem, discovered in the Plan 2 results, affects the ability of the reservoirs to meet low flow requirements at Anoka during monthly simulations. This problem was not identified until most of the computer analysis of the plans was completed and was not corrected by HEC until after the St. Paul District decided that Anderson-Nichols should wait no longer to complete the computer analysis of all of the plans. Therefore, the HEC-5 problem is present in the results of Plans 2, 5, and 6, and its effects on these results are discussed in the appropriate section for each plan.



Bemidji Lake
Winnibigoshish Lake
Cass Lake
Lake Itasca
CLEARWATER
HUBBARD
Leech Lake River
Pokegama Lake
Walker
Leech Lake
Mud Lake
ITASCA
Park Rapids
Grand Rapids
Cohasset
Prairie River
CASS
BECKER
Pine River Lake
Libby
Sandy Lake
CARLTON
PINE
AITKIN
Aitkin
Gull Lake
Wadena
WADENA
TODD
Crow Wing River
Brainerd
Riverton
CROW WING
Mille Lacs Lake
OTTER TAIL
MORRISON
Long Prairie
Little Falls
Royalton
MISSISSIPPI RIVER
DOUGLAS
STEARNS
MILLE LACS
Milaca
Rum River
ISANTI
BENTON
SHERBURNE
POPE
North Sauk River
St Cloud
Becker
Elk River
Monticello
MEEKER
Fort Crow River
KANDIYOHI
Litchfield
HENNEPIN
Anoka
ANOKA
RAMSEY
WASHINGTON
Minneapolis
St Paul
WRIGHT
South Fork Crow
MC LEOD
RENVILLE
CARVER
Minnesota R
DAKOTA CO
CANADA
BASIN AREA
DULUTH
MINNEAPOLIS
ST PAUL
WIS
IOWA
LOCATION MAP
LEGEND
Corps Dams
STREAMFLOW GAGING STATIONS
0 10 20 30
SCALE IN MILES
GENERAL MAP
UPPER MISSISSIPPI RIVER BASIN
ABOVE THE MINNESOTA RIVER

FIGURE 1-1

GENERAL OPERATING DATA - MISSISSIPPI RIVER HEADWATERS RESERVOIRS



Rev. 7/81
Rev. 3/79

LAKE ELEVATIONS IN FEET - 1929 ADJ.						
RESERVOIR	WINNI-BIGOSHISH	LEECH	POKEGAMA	SANDY	PINE	GULL
NORMAL SPRING STAGE (DATE)	1296.94(3/1)	1293.20(3/1)	1270.42(3/15)	1214.31(2/15)	1227.32(2/15)	1192.75(2/15)
DESIRABLE SUMMER RANGE	1298.94-1299.44	1294.50-1294.90	1273.17-1273.67	1216.06-1216.56	1229.07-1229.57	1193.75-1194.00
ORIGINAL OPERATING LIMITS	1288.94-1303.14	1292.20-1297.94	1268.92-1276.42	1207.91-1218.31	1217.52-1234.82	1188.75-1194.75
CAPACITY, ORIGINAL OPERATING LIMITS, AC-FT	967,900	743,300	120,800	78,700	178,900	70,800
PRESENT OPERATING LIMITS	1294.94-1303.14	1292.70-1297.94	1270.42-1276.42	1214.31-1219.31	1225.32-1231.32	1192.75-1194.75
PRESENT ORDINARY OPERATING LIMITS	1296.94-1300.94	1293.20-1295.70	1270.42-1274.42	1214.31-1218.31	1226.32-1230.32	1192.75-1194.75
DESIRABLE OPERATING LIMITS	1296.94-1299.44	1293.20-1295.70	1271.42-1274.42	1214.31-1218.31	1227.32-1230.32	1192.75-1194.75
CAPACITY, PRESENT OPERATING LIMITS, AC-FT	653,600	689,800	102,400	37,600	79,900	26,000
FLOWAGE RIGHTS ACQUIRED TO ELEVATION OF	1306.94+	1301.70+	1280.42+	1222.31+	1238.82+	1198.75+
MAXIMUM ELEVATION EVER ATTAINED	1303.39	1297.88	1277.92	1224.82	1234.56	1195.05
NUMBER OF TIMES UPPER OPERATING LIMIT HAS BEEN EXCEEDED	2	0	18	18	0	8
NO. TIMES FLOWAGE LIMITS HAVE BEEN EXCEEDED	0	0	0	1	0	0
MAXIMUM ELEVATION ATTAINED 1950	1303.17	1296.81	1277.39	1224.82	1231.41	1195.01
RESERVOIR IN OPERATION	1884	1884	1884	1895	1886	1912

FIGURE 1-2

STAGES IN USE PRIOR TO JULY 1973						
RESERVOIR	WINNI-BIGOSHISH	LEECH	POKEGAMA	SANDY	PINE	GULL
NORMAL SPRING STAGE (DATE)	6.0 (3/1)	0.5 (3/1)	6.0 (3/15)	7.0 (2/15)	11.0 (2/15)	5.0 (2/15)
DESIRABLE SUMMER RANGE	10.0-10.5	1.8-2.2	8.75-9.25	8.75-9.25	12.75-13.25	6.0-6.25
ORIGINAL OPERATING LIMITS	0'-14.2'	-0.5'-5.24'	4.5'-12'	0.6'-11'	1.3'-18.5'	1.0'-7.0'
CAPACITY, ORIGINAL OPERATING LIMITS AC-FT	967,900	743,300	120,800	78,700	178,900	70,800
PRESENT OPERATING LIMITS	6'-14.2'	0'-5.24'	6'-12'	7'-11'	9-15.0	5'-7'
PRESENT ORDINARY OPERATING LIMITS	8'-12'	0.5'-3.0'	6'-10'	7'-11'	10'-14'	5'-7'
DESIRABLE OPERATING LIMITS	8'-10.5'	0.5'-3.0'	7'-10'	7'-11'	11'-14'	5'-7'
CAPACITY, PRESENT OPERATING LIMITS AC-FT	653,600	689,800	102,400	37,600	79,900	26,000
FLOWAGE RIGHTS ACQUIRED TO STAGE OF	18'+	9'+	16'+	15'+	22.5'+	11.0'+
MAXIMUM STAGE EVER ATTAINED	14.45'	5.16'	13.50'	17.51'	18.24'	7.3'
NUMBER OF TIMES UPPER OPERATING LIMIT HAS BEEN EXCEEDED	2	0	18	18	0	8
NO. TIMES FLOWAGE LIMITS HAVE BEEN EXCEEDED	0	0	0	1	0	0
MAXIMUM STAGE ATTAINED IN 1950	14.23'	4.11'	12.97'	17.51'	15.09'	7.26'
ZERO OF GAGE:						
(U.S.E. DATUM)	1290.06'	1293.76'	1265.27'	1209.00'	1218.20'	1190.00'
(M.S.L., 1912 ADJ.)	1289.47'	1293.23'	1264.89'	1207.70'	---	1188.14'
(M.S.L., 1929 ADJ.)	1288.94'	1292.70'	1264.42'	1207.31'	1216.32'	1167.75'
RESERVOIR IN OPERATION	1884	1884	1884	1895	1886	1912

TOP OF PIERS	15.42	6.84	14.0	14.0	19.5	10.0
SILL	-4.78	-4.96	0.00	0.00	+0.33	+1.0

FIGURE 1-3

SECTION 2

APPROACH

OVERVIEW

The analysis of alternative reservoir operation plans was performed using computer simulation. The Headwaters area of the Mississippi River Basin, ending at St. Paul, Minnesota, was represented by 11 control points (CP), river locations where hydrologic information is accumulated, as follows:

Reservoirs

CP1	Winnibigoshish
CP2	Leech
CP3	Pokegama
CP4	Sandy
CP7	Pine
CP8	Gull

River Stations

CP5	Libby
CP6	Aitkin
CP9	Royalton
CP10	Anoka
CP11	St. Paul

Control point location is shown on the basin map, Figure 2-1. A schematic diagram is shown in Figure 2-2. Hydrologic simulation was performed using HEC-5, Simulation of Flood Control and Conservation Systems. In general, simulation of a given reservoir operating plan proceeds in the following manner:

Input Data:

- Physical characteristics and operating parameters for each reservoir control point
- Parameters for each river station control point
- Routing parameters between control points
- Flow hydrographs at each control point (local flow from contributing area below next upstream control point)

Computation:

- Simulation is performed through the time period represented by flow hydrographs.
- Reservoir outflow hydrographs are based upon reservoir operating specifications contained in input data.

- Simulation begins at the most upstream station, Winnibigoshish, and proceeds downstream by routing the upstream control point computed hydrograph value to the next downstream control point, combining with the downstream control point's local flow hydrograph value for the current time period, routing to the next downstream control point, etc., and continuing until the computed hydrograph is developed for all control points for the current time period. Simulation proceeds in this manner through all time periods.

Output:

- Input data are organized and displayed.
- Reservoir conditions and release logic are displayed for each reservoir for all time periods.
- Flow hydrographs are displayed at each control point including natural flow (no reservoir regulation Plan 4 only), regulated flow (reservoirs operating), and local flow.

Computer simulation was performed for each alternative reservoir operating plan using monthly flow data for the period January 1930 through December 1976, 47 years (564 periods). During periods of extreme high flow, daily flow hydrographs (for an entire month, or months) were simulated to refine the monthly flow simulation results. This was performed for the single, largest flow event in each of the most extreme 20 years.

The hydrologic simulation was followed by a statistical analysis using expected probability and Weibull plotting positions (annual probability of exceedance) of the refined monthly time series results:

high stage at each of the six reservoirs,
low stage at each of the six reservoirs,
high flow at Aitkin, and
low flow at Anoka.

The frequency results were combined with damage data at the reservoirs and Aitkin in order to compute the total average annual damage for the given reservoir operating plan. The cost of water shortage at Anoka was computed by totaling the shortage in cfs-days for the period of record and applying a water cost factor.

COMPUTATIONAL SCHEME

Computer processing was performed on the HEC Harris 500 System via remote terminal. Simulation of each reservoir operating plan was performed using four primary programs plus a time series data management file system:

HEC-5	Hydrologic simulation (see Reference 3)
MERGE	Monthly and daily time series combination (see Appendix B)
FATSO	Exceedance frequency computation (see Appendix C)
EAD	Average Annual Damage Computation (see Reference 4)
HEC-DSS	Time series file management (see Appendix D)

Simulation computations for a given reservoir operating plan proceeded in the following manner:

Step 1 HEC-5 - Monthly flow simulation is performed for period of record 1930-1976. Time series results (elevation at reservoirs and flow at Aitkin and Anoka) are written to HEC-DSS.

Step 2 HEC-5 - Daily flow simulation is performed for each extreme event (20 events, one per year). The same time series results as Step 1 are written to HEC-DSS. Initial reservoir storage for each daily event is taken from results of monthly simulation in Step 1.

Step 3 MERGE - Monthly and daily time series results are read from HEC-DSS. Monthly simulation results are replaced by extreme daily simulation results for each month where both daily and monthly simulation were performed in Steps 1 and 2. Revised monthly simulation results are written to HEC-DSS.

Step 4 FATSO - Revised monthly time series are read from HEC-DSS. The following annual frequency relationships are computed (percent chance of exceedance):

- High Stage at Reservoirs (May-Sept only)
- Low Stage at Reservoirs (May-Sept only)
- High Flow at Aitkin
- Low Flow at Anoka

Step 5 PLOT - An HEC utility plot program is used to plot reservoir stage versus time for each reservoir and flow versus time for Aitkin and Anoka over the period of record, 1930-1976.

Step 6 EAD - Average annual damage is computed using frequency relationships generated at Step 4 plus given damage relationships:

- High Stage at Reservoirs
- Low Stage at Reservoirs
- High Flow at Aitkin

Average Annual Cost due to not meeting low flow requirements at Anoka are computed by totaling shortage, dividing by number of years of record and multiplying by a cost factor ($385 per cfs-day) (Reference 1, p. 34).

A schematic of the computation sequence is shown in Figure 2-3.

RESERVOIR OPERATION LOGIC

An explanation of the HEC-5 decision criteria for determining reservoir releases is contained in the Users Manual (see Reference 3, pp. 12-18, and Exhibit 3). For this study, five index levels (reservoir storage levels) are used:

Level 5 - Top of Flood Control Pool

Level 4 - Top of Conservation Pool

Level 3 - Reservoir Balancing Level used to bring reservoirs to summer target level

Level 2 - Top of Buffer Pool

Level 1 - Top of Inactive Pool

In general, reservoirs operate to satisfy downstream requirements such as flood prevention or maintenance of specified minimum flows as well as specific requirements at the reservoir including keeping a system of two or more reservoirs in balance (based upon equal index levels). Reservoir operation is performed within the specified physical constraints at the reservoir site. Briefly, the following release rules apply:

Pool	Between Index Levels	Rule
Buffer	1-2	Releases are made equal to or greater than minimum required flow
Conservation	2-4	Releases are made equal to or greater than minimum desired flow
Flood Control	4-5	Releases are only made if they will not contribute to downstream flooding (Level 4 is the target level; where possible, reservoir levels are maintained at this target by adjusting releases)
Surcharge	Above 5	Releases are made up to outlet capacity to bring index level back to 5 as quickly as possible.

LOCAL FLOW HYDROGRAPHS

The local flow hydrographs at each control point used during computer simulation were the same as used by SAFHL during their previous study. The reservoir inflow hydrographs were developed by SAFHL using a reverse routing procedure based upon storage and outflow records (see Reference 2). The SAFHL Study simulated reservoir operation during the period January 1932 through December 1976.

The critical low-flow period occurs from 1930-1938; therefore, this study initiated simulation in January 1930. SAFHL had developed reservoir inflow hydrographs (monthly) for 1930 and 1931 using the same procedure as used to compute values from 1932-1976. These hydrographs were used. The remaining local flow hydrographs for 1930 and 1931 were developed during this study.

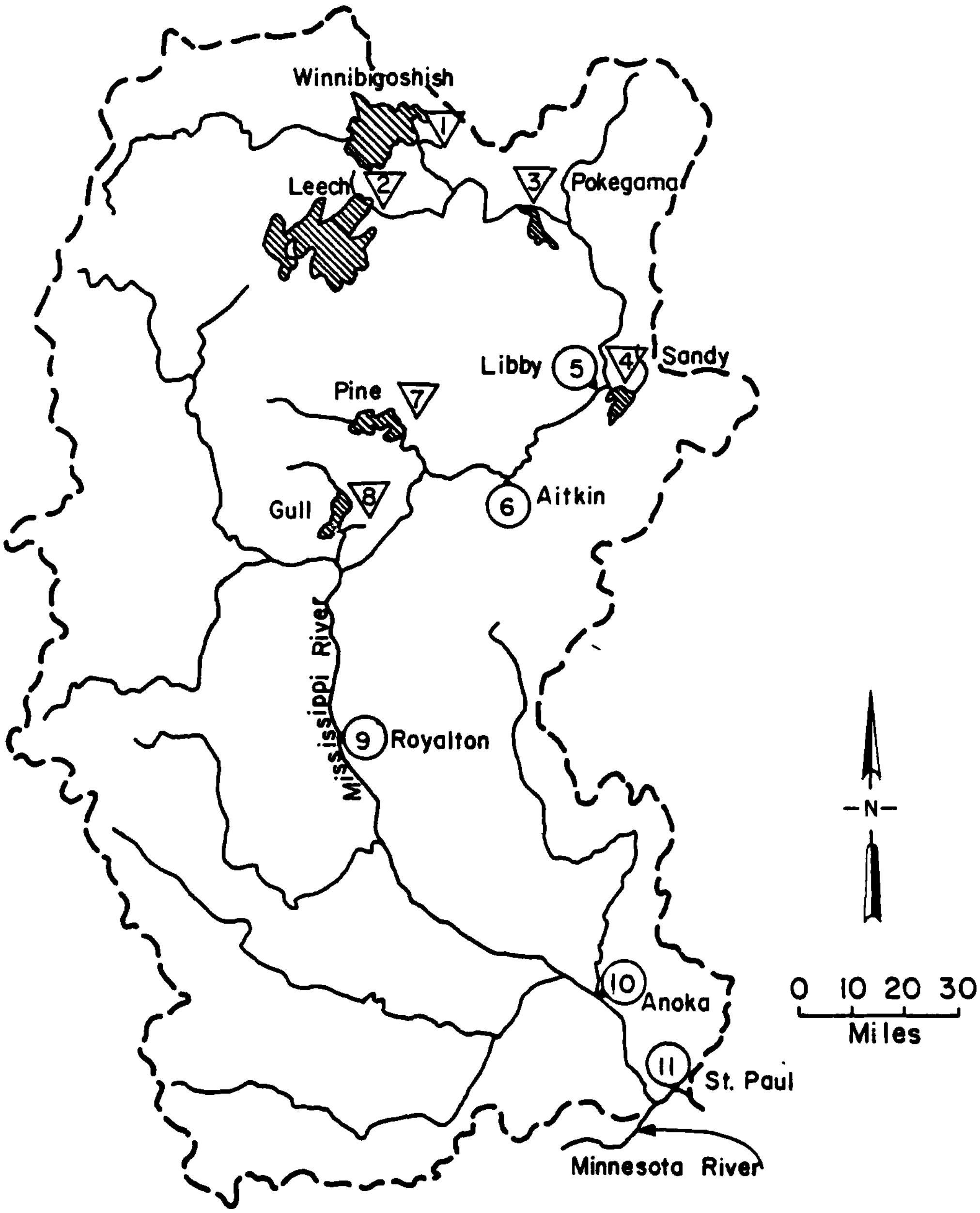
Local flow values for 1930 and 1931 were developed at Anoka and Aitkin since direct gage data was not available. The Anoka flows are based on USGS data at Elk River, St. Paul, and Mankato. Flows at Anoka were calculated using an average of the proportional area relationships between the three USGS stations and Anoka. This equation is:

$$\text{Anoka} = 0.5\ [1.08\ (\text{Elk R}) + 0.86\ (\text{St. Paul-Mankato})]$$

An attempt was made to compute Aitkin flows in a similar manner using USGS data at Libby (below Sandy), Royalton, and Elk River. These relationships produce too much variability; therefore, this method was

not used. Flow at Aitkin was determined by multiplying the average unit area flow (cfs/mi^2) of the three USGS stations by the tributary area at Aitkin.

The results of this process plus gage records at Libby, Royalton, and St. Paul provided the remaining cumulative flow hydrographs. Local flow hydrographs (monthly) were then computed for each control point by subtracting the next upstream control point cumulative hydrograph (or sum of multiple upstream hydrographs if two or more control points are directly routed to the downstream control point) from the downstream control point cumulative hydrograph. When the upstream control point is a reservoir, the reservoir outflow hydrograph (actual) was used.



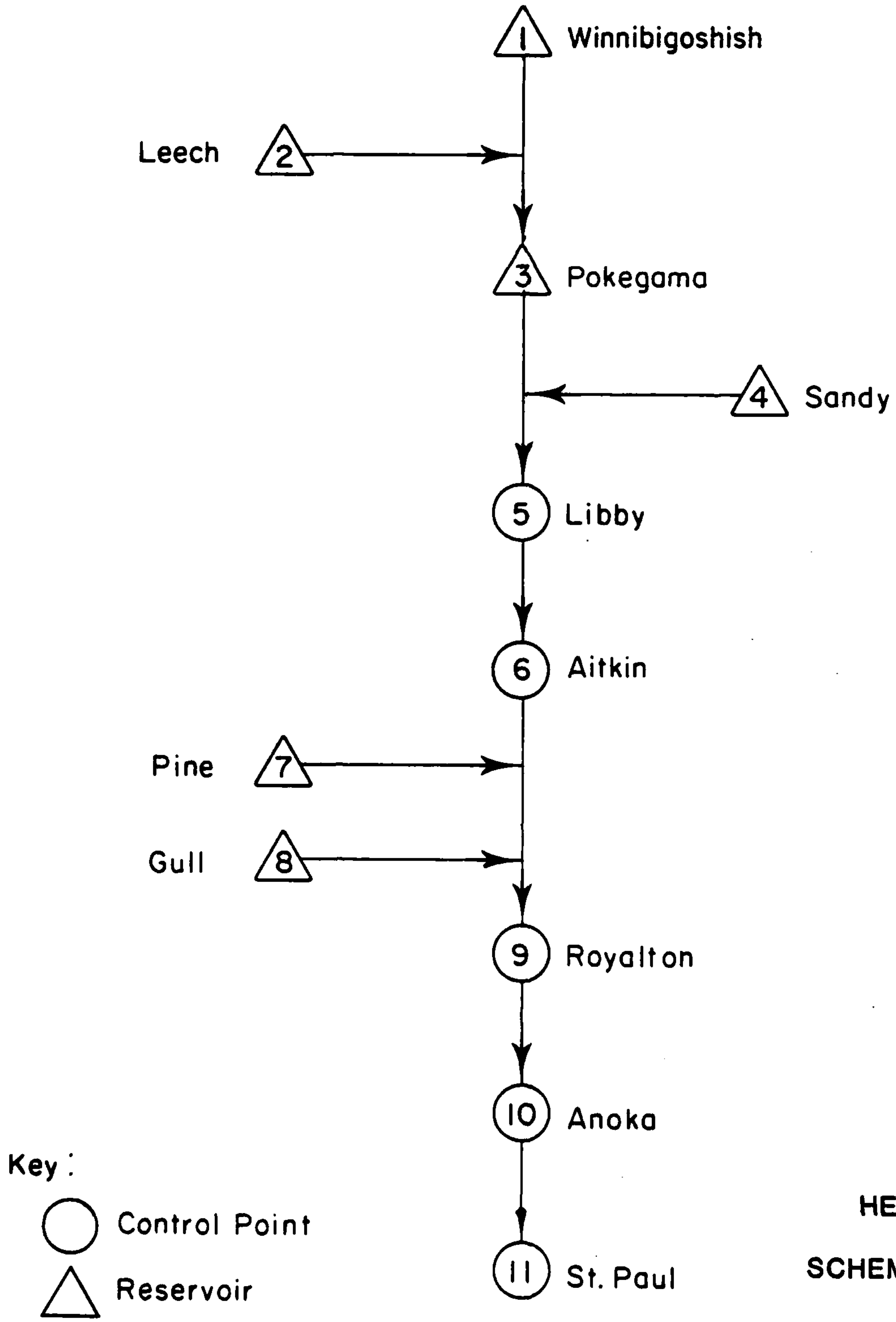
Key:

◯ Control Point

▽ Reservoir

MISSISSIPPI RIVER HEADWATERS
BASIN MAP

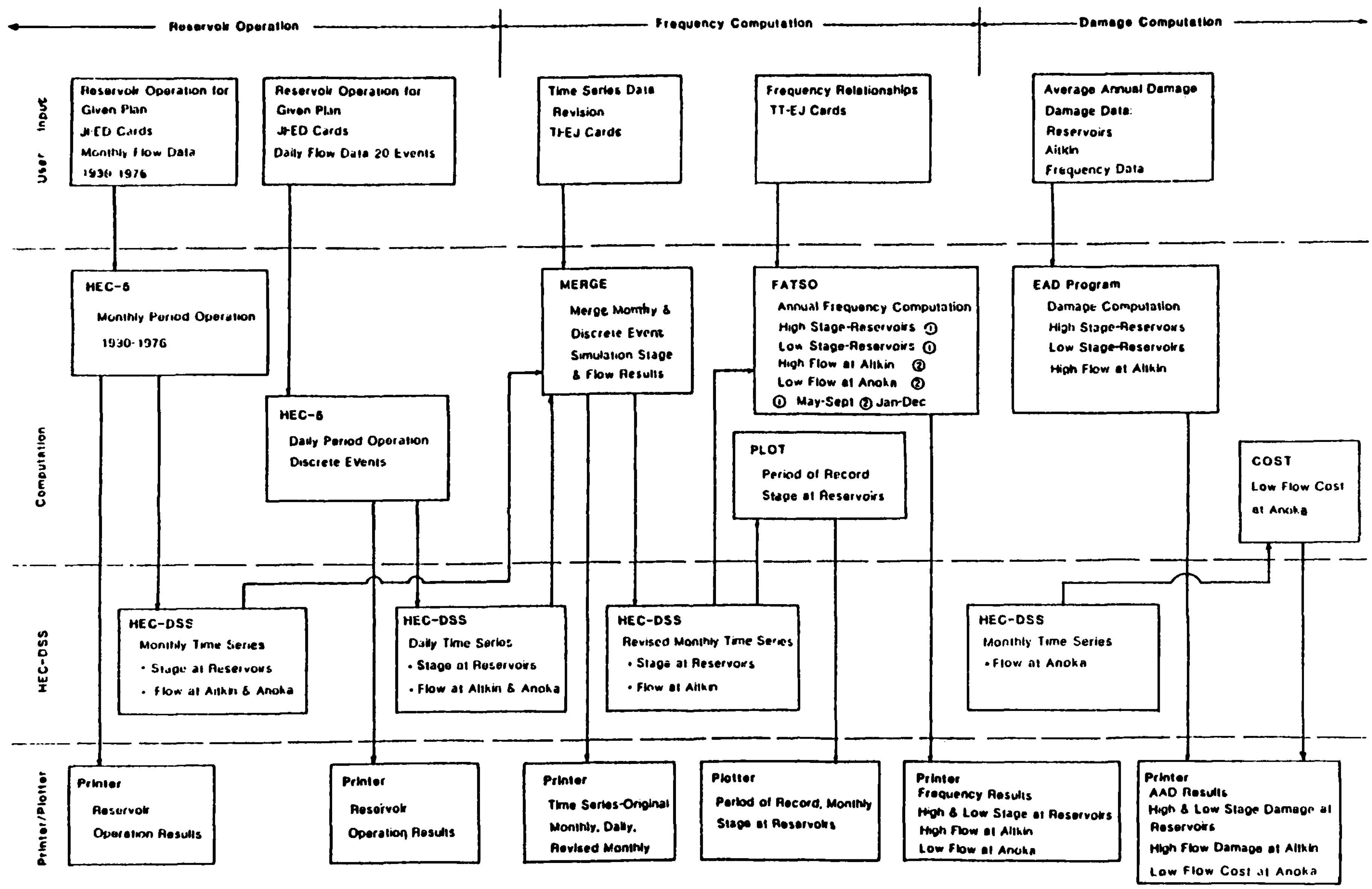
FIGURE 2-1



HEC-5 MODEL

SCHEMATIC DIAGRAM

FIGURE 2-2



Computational Sequence Schematic Diagram

Figure 2-3

SECTION 3

CRITERIA

This section provides criteria used in the computer simulation and analysis which generally applies to all alternative reservoir operating plans. Criteria which are plan specific are described in the appropriate Sections, 4 through 14.

RESERVOIR DATA

Reservoir criteria include data describing physical capacity and outlet capacities as well as operational criteria.

Reservoir Operation Control Points

During the HEC-5 simulation modeling, all reservoirs are operated for criteria and constraints at their location (reservoir control point criteria). In addition, certain reservoirs are operated to satisfy downstream control point conditions as follows:

Reservoir Control Point	Operated for	Reason
1 Winnibigoshish	3 Pokegama	Tandem reservoir operated to keep the three reservoir system (Winni, Leech, and Pokegama) in balance. Applies to all plans except Natural Plan, Plan 4.
2 Leech	3 Pokegama	Same as above.
3 Pokegama	6 Aitkin	Flood control requirements at Aitkin. Operates to keep total flow at Aitkin below channel capacity. All plans except Natural Plan, Plan 4, and Minimize Lake Property Damage Plan, Plan 8.
	10 Anoka	Low flow requirements at Anoka. Operates to maintain flow at or above low-flow requirement for Plan 2, 1,600 cfs; Plan 5, 2,275 cfs; Plan 6, 4,800 cfs.
4 Sandy	6 Aitkin	Flood control requirement at Aitkin, same as Pokegama operation.

Initial Storage

The initial reservoir storage values in January 1930 were set to the given plan target level specified by index Level 3 and 4 (index Levels 3 and 4 are always set at same elevation in January). This would be the expected level if the given plan criteria had governed reservoir operation

in 1929 which was a relatively normal year. The initial reservoir storage values for daily simulation events were set to the end-of-period value for the previous month which was computed during the monthly simulation for the given plan.

Minimum Desired Flow, Minimum Required Flow

HEC-5 makes reservoir releases to keep flows at or above the minimum desired flow until reservoir storage diminishes to Level 2. The reservoirs keep flows at or above the minimum required flow until storage drops to Level 1. The minimum required flow at Anoka is dependent on the specific operating plan. These flow requirements are listed in Table 3-1.

TABLE 3-1

MINIMUM DESIRED FLOW, MINIMUM REQUIRED FLOW

Reservoir	Minimum Desired Flow (cfs)	Minimum Required Flow (cfs)
Winnibigoshish	100	50
Leech	100	50
Pokegama	200	100
Sandy	20	10
Pine	30	10
Gull	20	10
Low Flow Plans		
Anoka, Plan 2		1,600
Anoka, Plan 5		2,275
Anoka, Plan 6		4,800

Reservoir Forecast/Contingency

Reservoir releases for daily flows are based upon forecasted conditions four periods in the future with a 10 percent contingency allowance for forecast error. This criteria is used for daily flow simulation.

Reservoir Outflow, Maximum Rate of Change

The maximum rate of change of reservoir outflow from one period to the next is equal to 50 percent of the downstream channel capacity under normal operating conditions. This criteria is used for daily flow simulation.

Reservoir Area - Capacity Curves

Reservoir elevation versus area versus storage capacity curves are shown on Figures 3-1 through 3-6.

Reservoir Elevation - Discharge Capacity Curves

Reservoir elevation versus maximum discharge capacity of outlet works is shown on Figures 3-7 through 3-12.

RIVER DATA

Routing Criteria

The routing of daily streamflow between control points uses the straddle-stagger method. The number of ordinates to be straddled and staggered for each channel reach are shown in Table 3-2. No routing is performed for monthly flow period simulation.

TABLE 3-2: ROUTING CRITERIA VALUES

Upstream Control Point	Downstream Control Point	Straddle Stagger Criteria (Ordinates Straddle. Ordinates Staggered)
1	3	5.3
2	3	5.3
3	5	3.1
4	5	1*
5	6	1.1
6	9	4.2
7	9	5.2
8	9	3.2
9	10	2.4
10	11	1.1

*There is no routing between 4 and 5 (Sandy and Libby). The distance is too short.

Channel Capacity

For each control point, a nondamage maximum channel capacity is specified. The program will use all upstream reservoirs (specified to operate for the given control point) to prevent or reduce flows beyond the channel capacity, until Level 5 (top of flood control pool) is reached. When any reservoir reaches Level 5, it increases discharge to stay at or below Level 5. Channel capacities are listed in Table 3-3.

TABLE 3-3

CHANNEL CAPACITY

Reservoir Outlets:			
Winnibigoshish	Outlet	Channel	2,000 cfs
Leech	"	"	1,500 cfs
Pokegama	"	"	6,000 cfs
Sandy	"	"	1,000 cfs
Pine	"	"	1,620 cfs
Gull	"	"	950 cfs
River Stations:			
Libby			no max specified
Aitkin			11,200 cfs
Royalton			no max specified
Anoka			no max specified
St. Paul			no max specified

No maximum channel capacities were established for Libby, Royalton, Anoka, and St. Paul because reservoir operation is not based upon high flow conditions at these control points.

Aitkin Stage - Discharge Curve

Figure 3-13 is a log-log plot of the rating curve for the Mississippi River at Aitkin based on published data from the U.S. Geological Survey. The datum of the stage recorder was lowered three feet on 30 September 1967 to eliminate negative stage readings. This relationship reflects stage versus total flow in the river and diversion channel.

ECONOMIC DATA

The economic data provides a means to compare damages at the 6 lakes and Aitkin and water shortage cost associated with low flow requirements at Anoka.

Stage-Damage at Reservoirs

The stage-damage at the six reservoirs was taken from the figures presented in the SAFHL Report. Elevation-damage curves were derived using 1977 prices and show both low and high water damage relationships. These reservoir stage damage curves are presented in Figures 3-14 through 3-19.

Stage-Damage at Aitkin

The stage-damage relationship at Aitkin has been modified by the St. Paul District from that used in the SAFHL Study. The curve is a composite of rural crop damages for each month during the growing season plus urban area damages. This damage curve is shown in Figure 3-20. The channel capacity used by HEC-5 for flood control operation by reservoirs is 11,200 cfs (approximately 15.0 ft stage which is the nondamage stage for urban damages).

Low Flow Cost at Anoka

The Anoka low flow cost is based on the cost to the Twin Cities area for water supply if flows drop below the low flow plan requirements at Anoka. The cost is calculated using the value of $385 per cfs-day for water that must be supplemented to maintain the required flow. This is equivalent to $0.60 per 1,000 gallons, which is the consumer cost of Minneapolis water supplied to customers outside of the city (Reference 1, p. 34). For a given plan, the total cost for the simulated period of record is divided by the total number of years (47 years) to arrive at the average annual cost. For each low flow plan (Plans 2, 5, and 6), this cost can be compared to the Anoka low flow cost computed for Plan 1 based upon the same low flow requirement to determine the net benefit (cost reduction). This benefit can then be compared to the increase in average annual damage at the reservoirs and Aitkin (difference between low flow plan and Plan 1) which is caused by operating Winnibigoshish, Leech, and Pokegama for the low flow requirement.

FLOW DATA

As explained in Section 2, simulation was performed for both monthly flow data and selected daily flow periods for the 20 largest annual events. The flow hydrographs were the same as used by SAFHL (Reference 1) except the monthly flow values for the years 1930 and 1931. Table 3-4 provides the time periods for each set of flow data. Daily data is used for each day in specified month.

TABLE 3-4: TIME PERIODS FOR HEC-5 FLOW DATA

Monthly Periods

1/30 - 12/76

Daily Periods

5/38	4-5/48	4-5/56	4-5/70
4-5/41	4-6/50	4-6/65	4-5/71
6-7/43	4-8/52	4-5/66	4-5/72
6-7/44	7-8/53	4-5/67	4-6/74
3-5/45	4-6/54	4-5/69	4-5/75

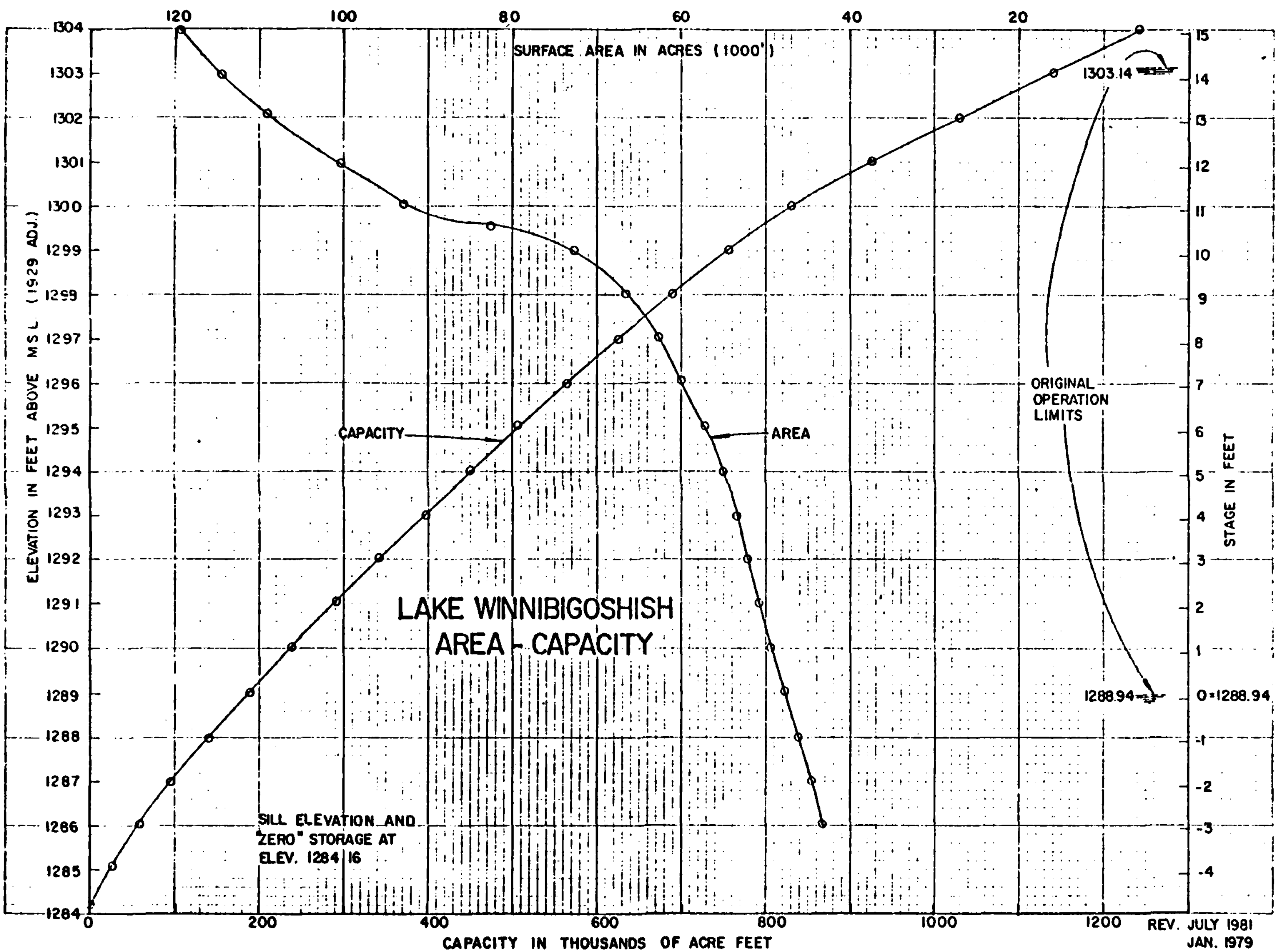

LAKE WINNIBIGOSHISH
AREA - CAPACITY
SURFACE AREA IN ACRES (1000')
120
100
80
60
40
20
ELEVATION IN FEET ABOVE MSL (1929 ADJ.)
1304
1303
1302
1301
1300
1299
1298
1297
1296
1295
1294
1293
1292
1291
1290
1289
1288
1287
1286
1285
1284
CAPACITY IN THOUSANDS OF ACRE FEET
0
200
400
600
800
1000
1200
STAGE IN FEET
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0=1288.94
-1
-2
-3
-4
CAPACITY
AREA
ORIGINAL OPERATION LIMITS
1303.14
1288.94
SILL ELEVATION AND "ZERO" STORAGE AT ELEV. 1284.16
REV. JULY 1981
JAN. 1979

FIGURE 3-1

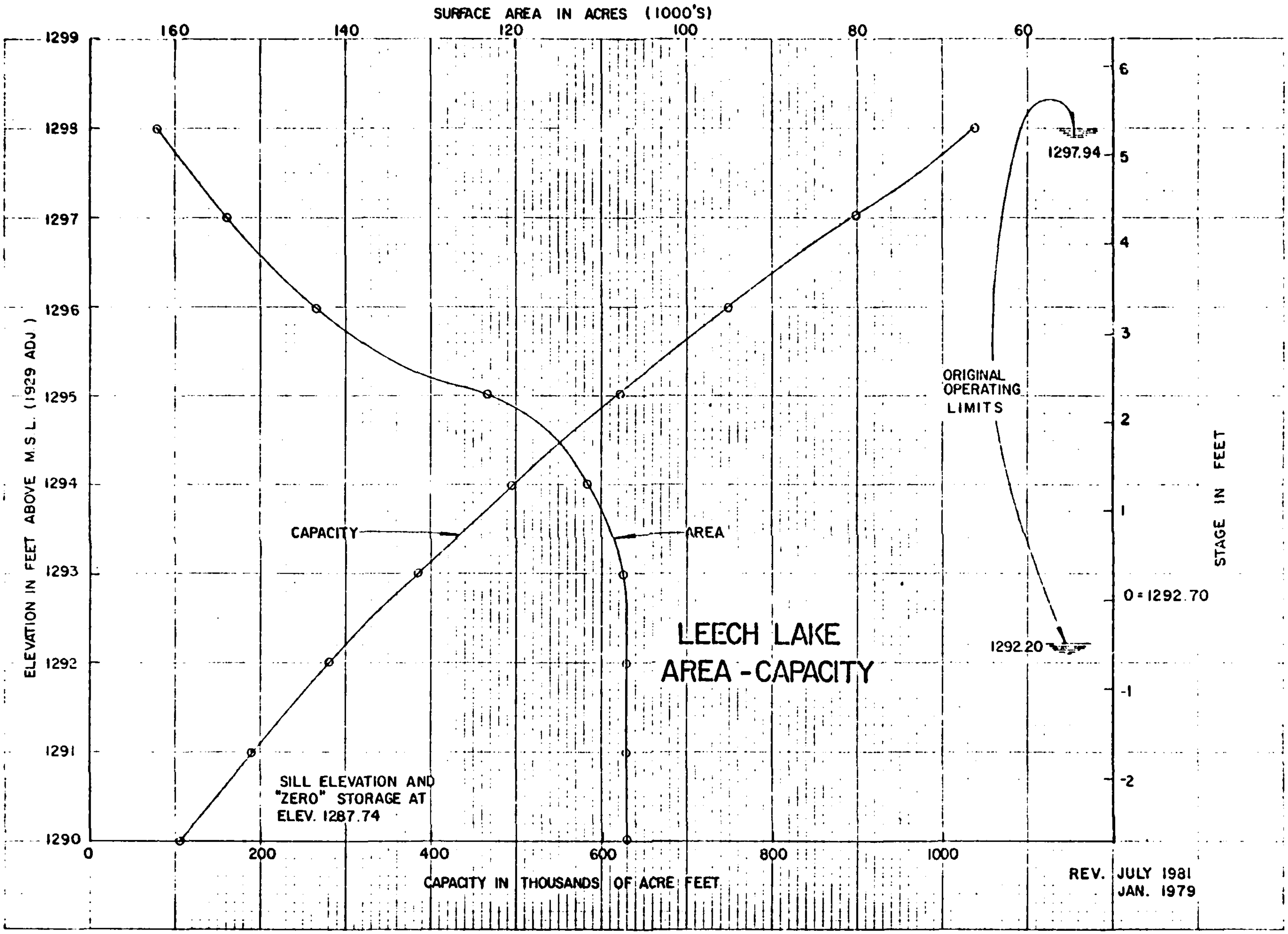

SURFACE AREA IN ACRES (1000'S)
160
140
120
100
80
60
1299
1298
1297
1296
1295
1294
1293
1292
1291
1290
ELEVATION IN FEET ABOVE M.S.L. (1929 ADJ)
0
200
400
600
800
1000
CAPACITY IN THOUSANDS OF ACRE FEET
6
5
4
3
2
1
-1
-2
STAGE IN FEET
0 = 1292.70
1297.94
1292.20
ORIGINAL
OPERATING
LIMITS
CAPACITY
AREA
LEECH LAKE
AREA - CAPACITY
SILL ELEVATION AND
"ZERO" STORAGE AT
ELEV. 1287.74
REV. JULY 1981
JAN. 1979

FIGURE 3-2

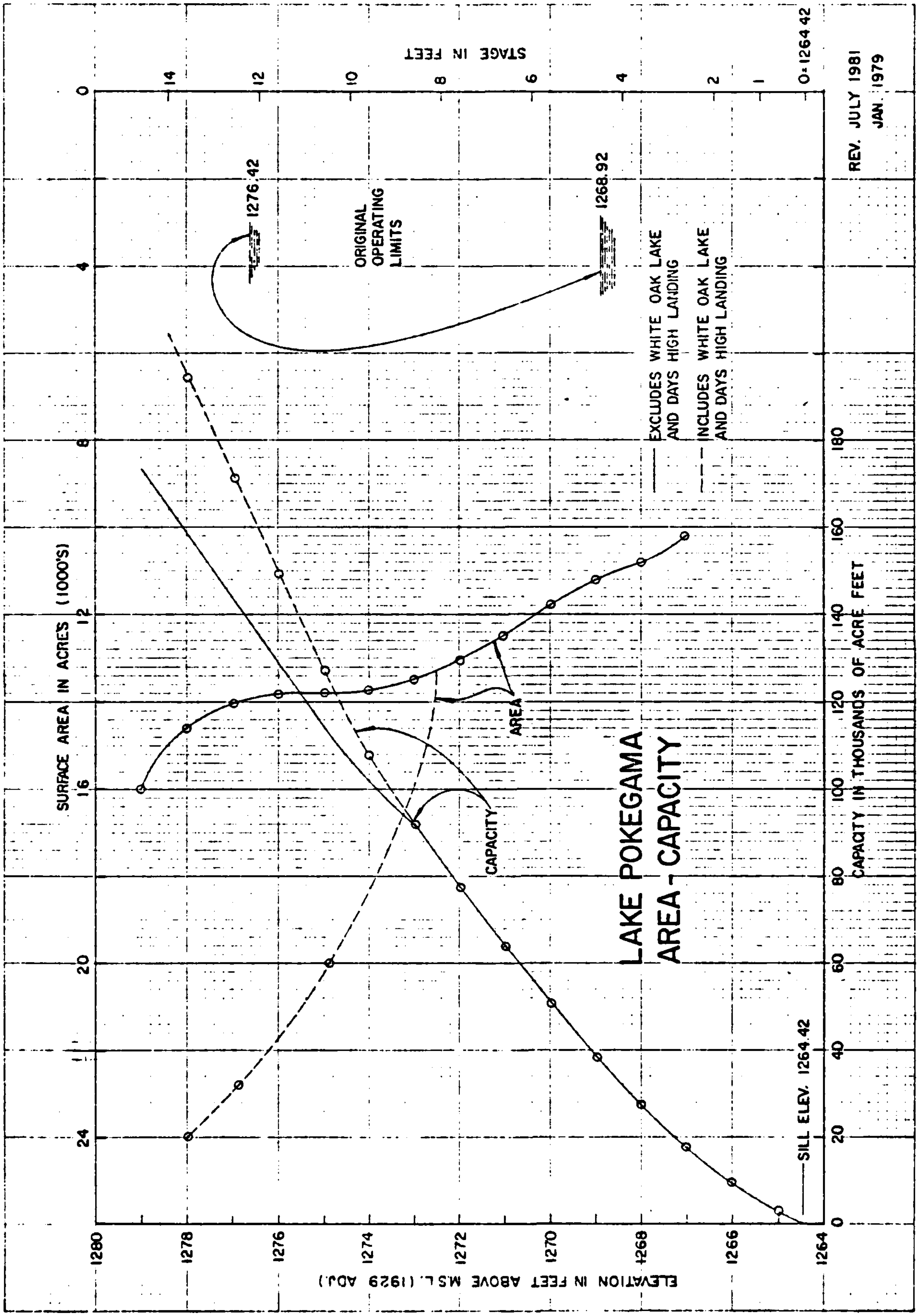

LAKE POKEGAMA
AREA - CAPACITY
SURFACE AREA IN ACRES (1000'S)
CAPACITY IN THOUSANDS OF ACRE FEET
ELEVATION IN FEET ABOVE M.S.L. (1929 ADJ.)
STAGE IN FEET
0=1264.42
ORIGINAL OPERATING LIMITS
1276.42
1268.92
EXCLUDES WHITE OAK LAKE AND DAYS HIGH LANDING
INCLUDES WHITE OAK LAKE AND DAYS HIGH LANDING
AREA
CAPACITY
SILL ELEV. 1264.42
REV. JULY 1981
JAN. 1979

FIGURE 3-3

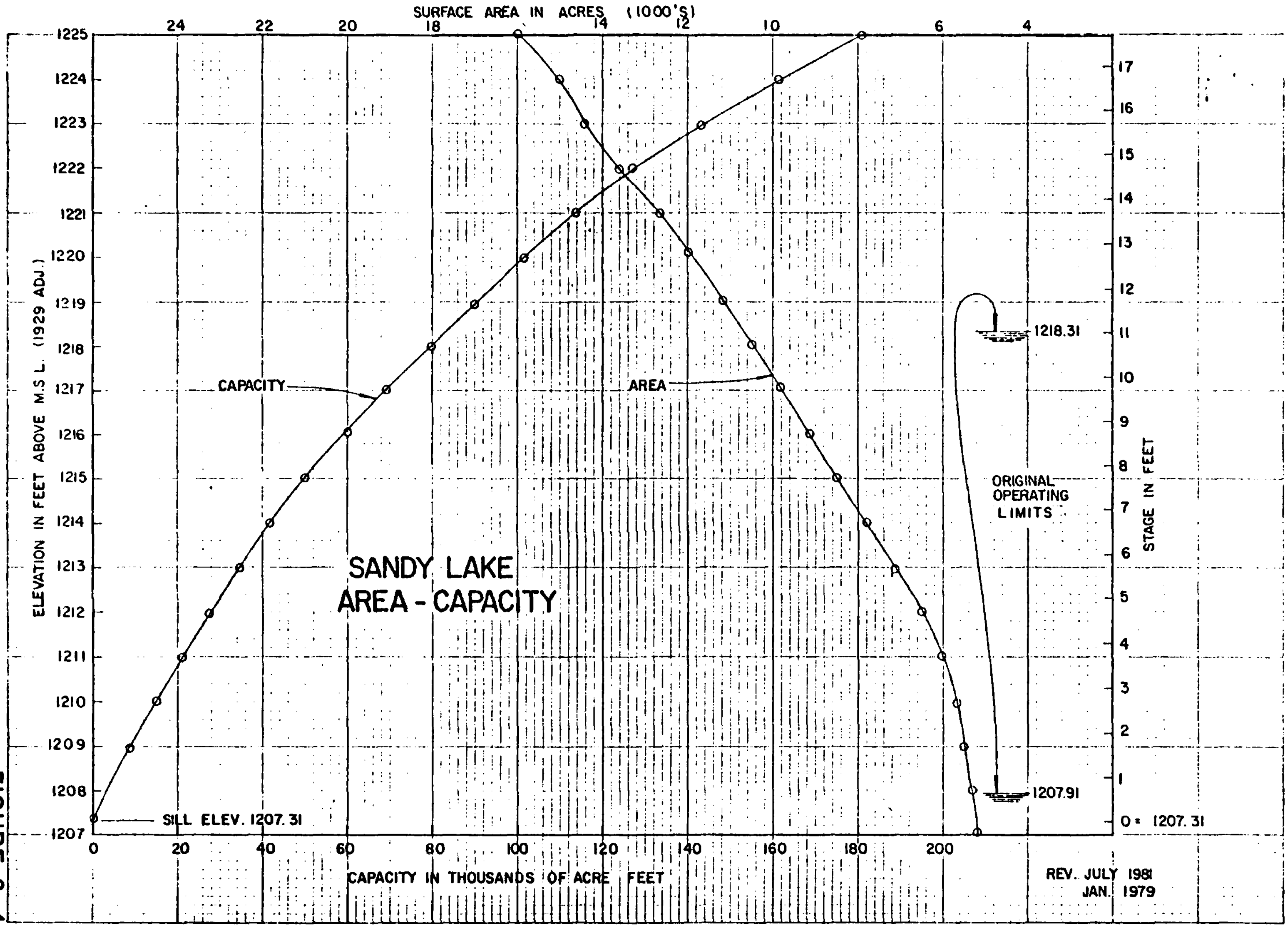

SURFACE AREA IN ACRES (1000'S)
24
22
20
18
14
12
10
6
4
1225
1224
1223
1222
1221
1220
1219
1218
1217
1216
1215
1214
1213
1212
1211
1210
1209
1208
1207
ELEVATION IN FEET ABOVE M.S L. (1929 ADJ.)
CAPACITY
AREA
SANDY LAKE
AREA - CAPACITY
1218.31
1207.91
ORIGINAL OPERATING LIMITS
SILL ELEV. 1207.31
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0 = 1207.31
STAGE IN FEET
0
20
40
60
80
100
120
140
160
180
200
CAPACITY IN THOUSANDS OF ACRE FEET
REV. JULY 1981
JAN. 1979

FIGURE 3-4

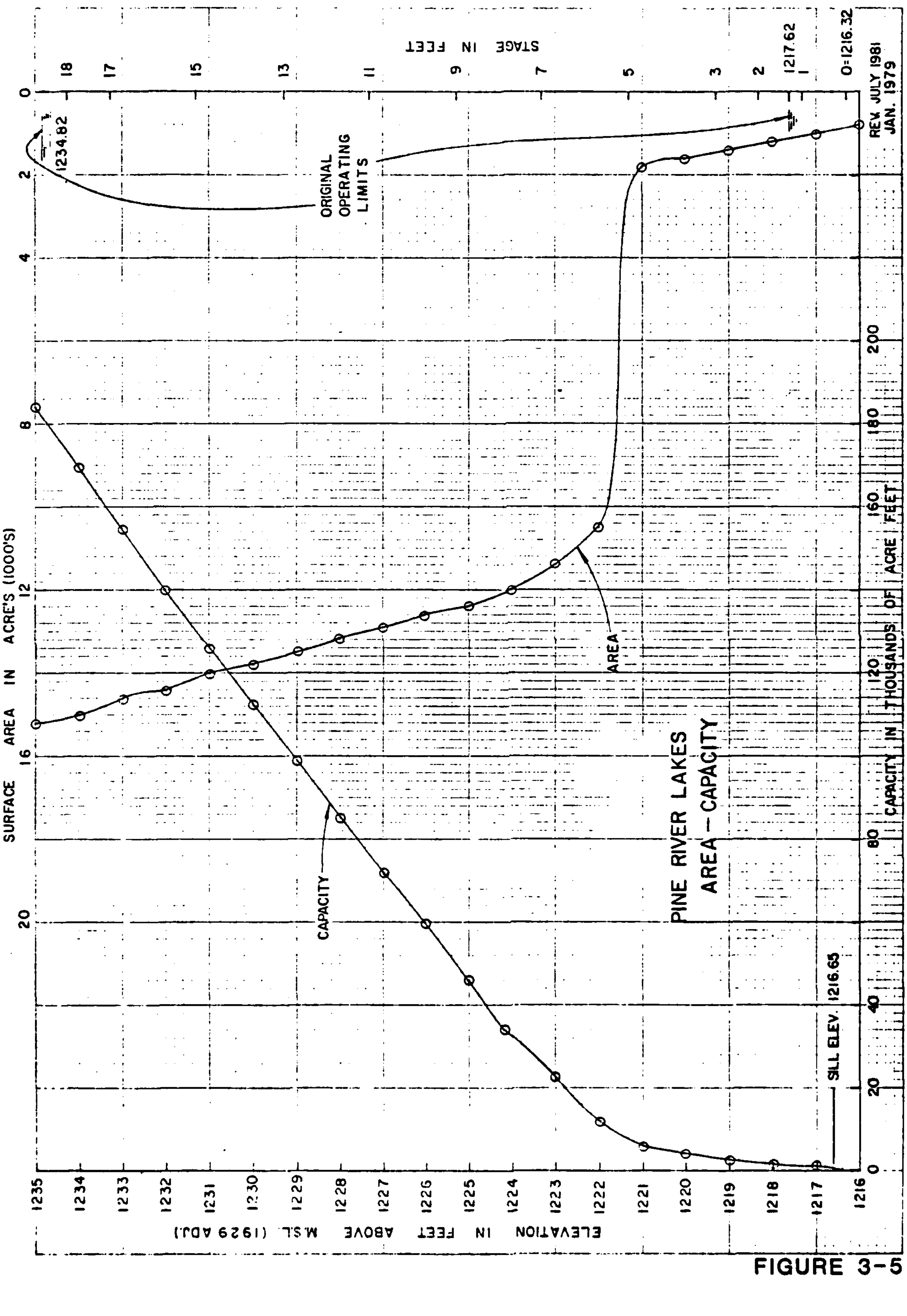
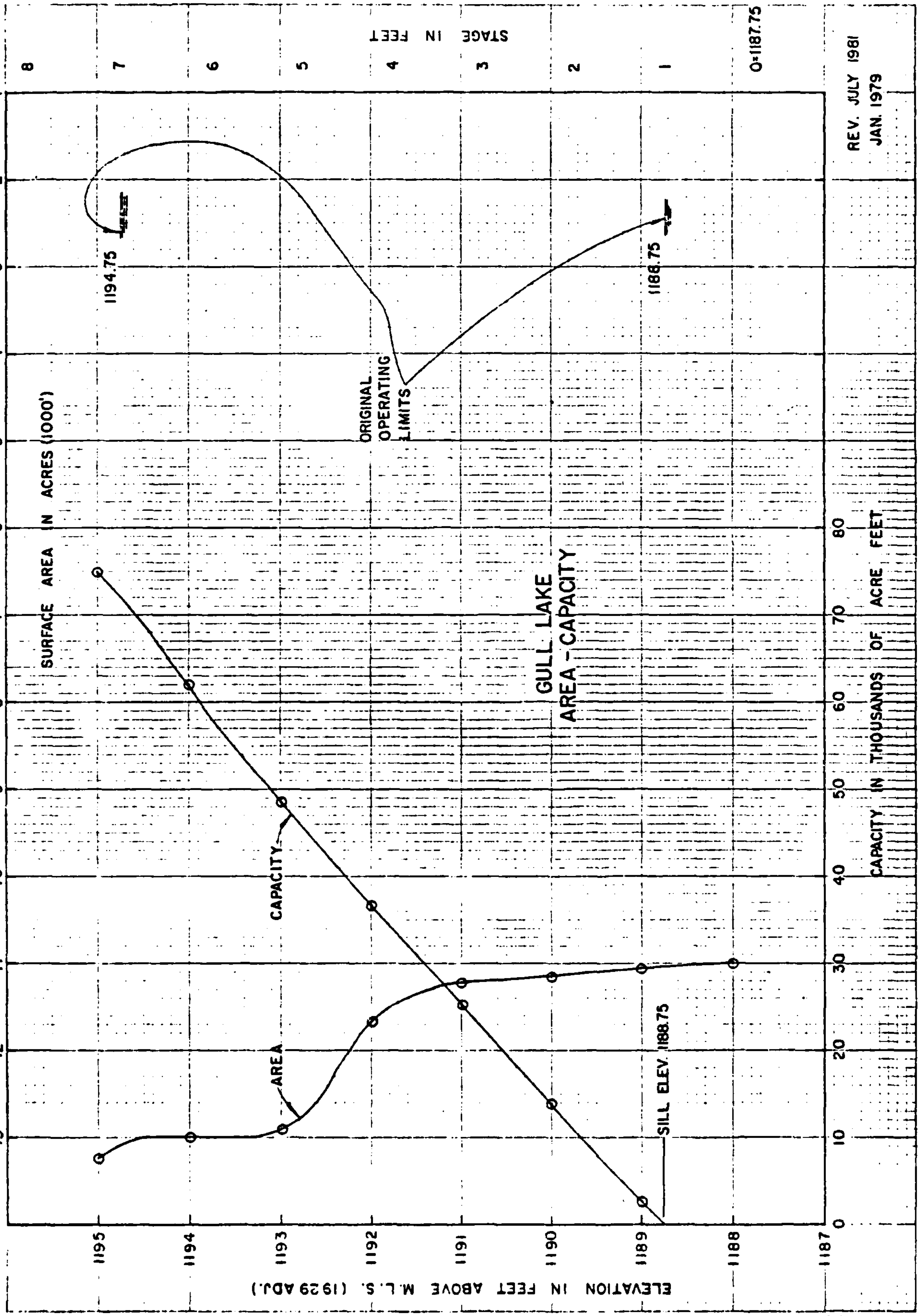
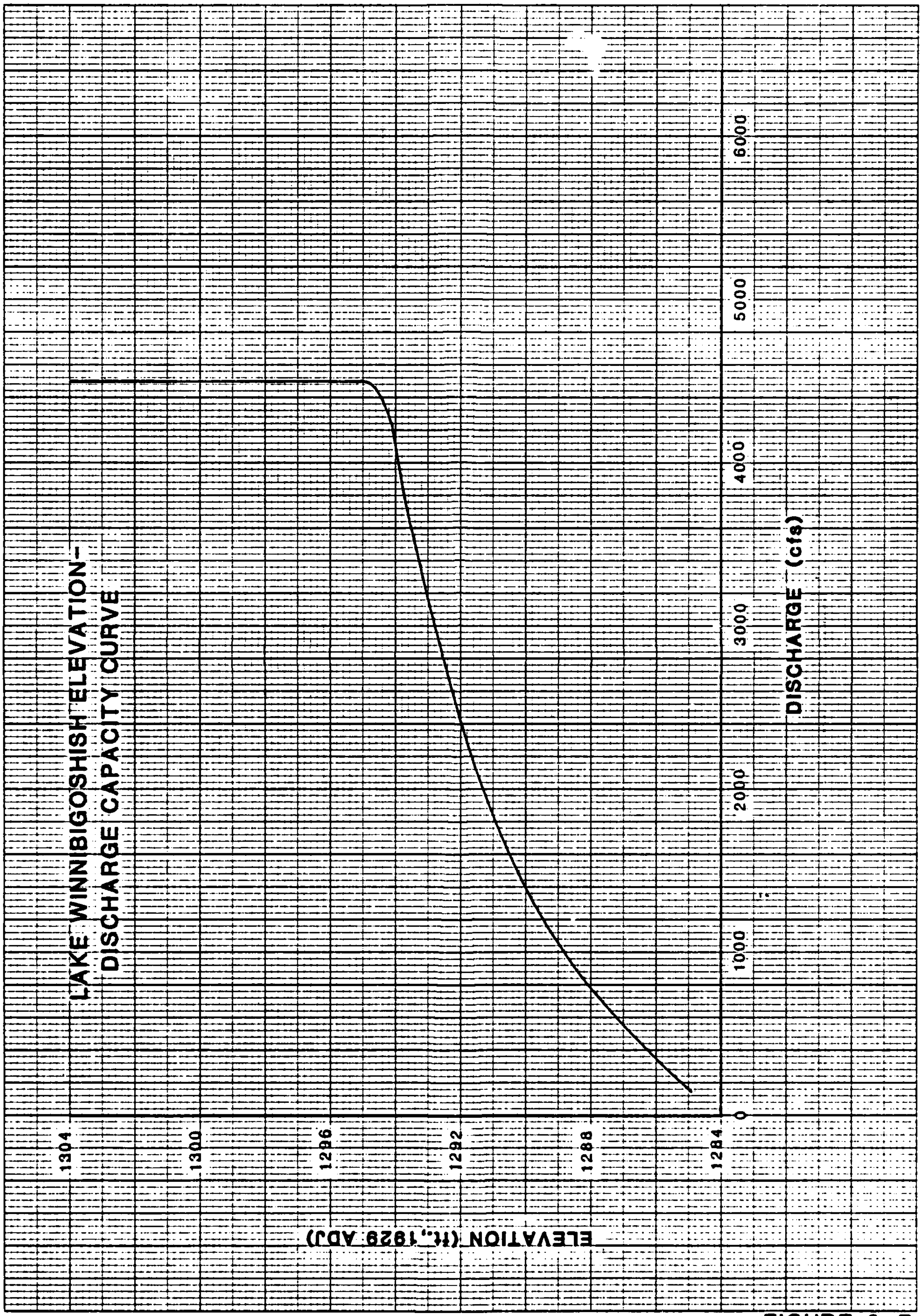

PINE RIVER LAKES
AREA — CAPACITY
SURFACE AREA IN ACRE'S (1000'S)
CAPACITY IN THOUSANDS OF ACRE FEET
ELEVATION IN FEET ABOVE M.S.L. (1929 ADJ.)
STAGE IN FEET
ORIGINAL OPERATING LIMITS
1234.82
1217.62
0=1216.32
SILL ELEV. 1216.65
AREA
CAPACITY
REV. JULY 1981
JAN. 1979

FIGURE 3-5



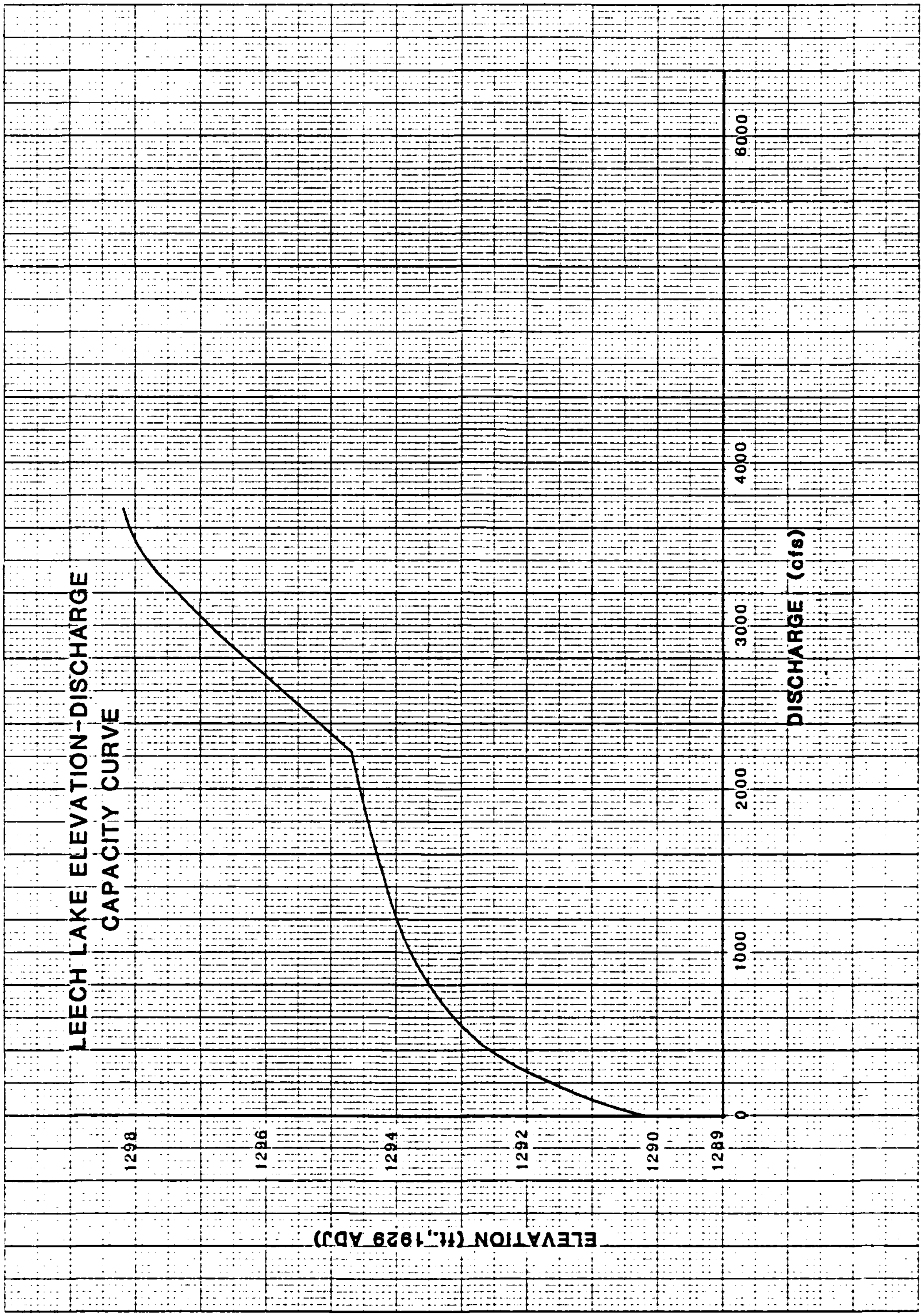
GULL LAKE
AREA-CAPACITY
SURFACE AREA IN ACRES (1000')
CAPACITY IN THOUSANDS OF ACRE FEET
ELEVATION IN FEET ABOVE M.L.S. (1929 ADJ.)
STAGE IN FEET
0=1187.75
ORIGINAL OPERATING LIMITS
1194.75
1188.75
SILL ELEV. 1188.75
CAPACITY
AREA
REV. JULY 1981
JAN. 1979

FIGURE 3-6



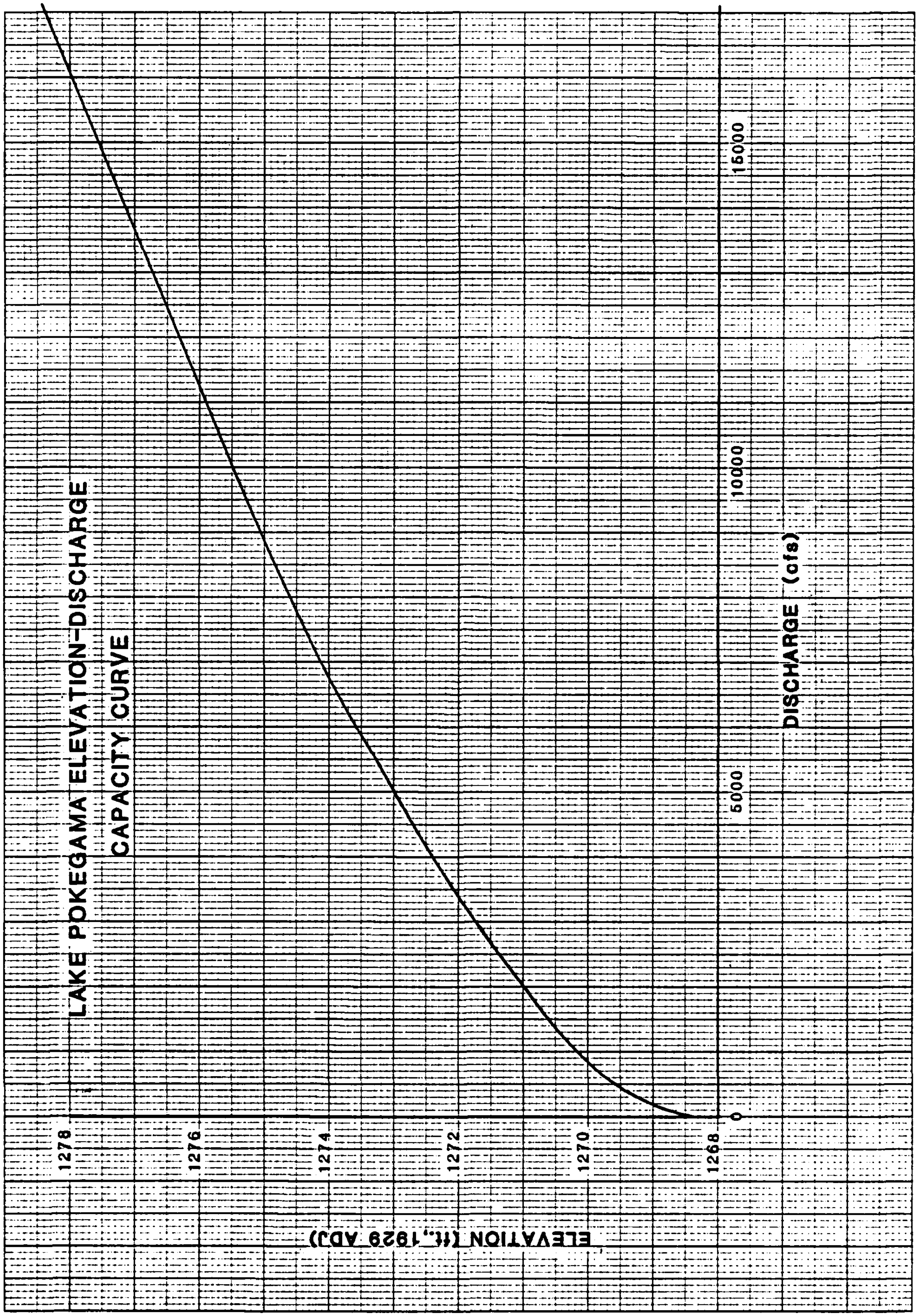
LAKE WINNIBIGOSHISH ELEVATION–
DISCHARGE CAPACITY CURVE
DISCHARGE (cfs)
0
1000
2000
3000
4000
5000
6000
ELEVATION (ft., 1929 ADJ)
1284
1288
1292
1296
1300
1304

FIGURE 3-7



LEECH LAKE ELEVATION-DISCHARGE
CAPACITY CURVE
DISCHARGE (cfs)
0
1000
2000
3000
4000
6000
ELEVATION (ft. 1929 ADJ)
1289
1290
1292
1294
1296
1298

FIGURE 3-8



LAKE POKEGAMA ELEVATION-DISCHARGE
CAPACITY CURVE
DISCHARGE (cfs)
0
5000
10000
15000
ELEVATION (ft. 1929 ADJ)
1268
1270
1272
1274
1276
1278

FIGURE 3-9

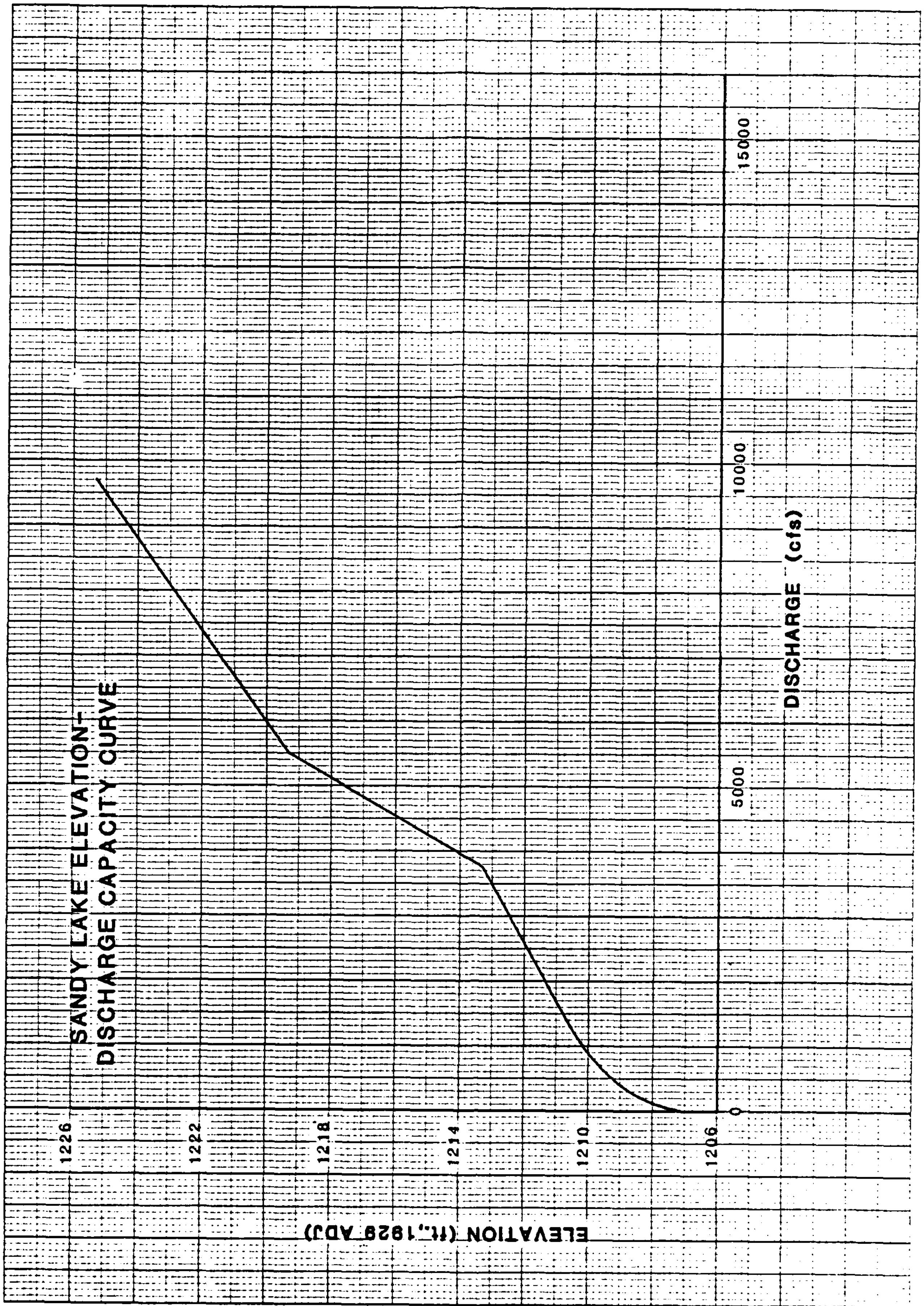

SANDY LAKE ELEVATION-
DISCHARGE CAPACITY CURVE
DISCHARGE (cfs)
0
5000
10000
15000
ELEVATION (ft.,1929 ADJ)
1206
1210
1214
1218
1222
1226

FIGURE 3-10

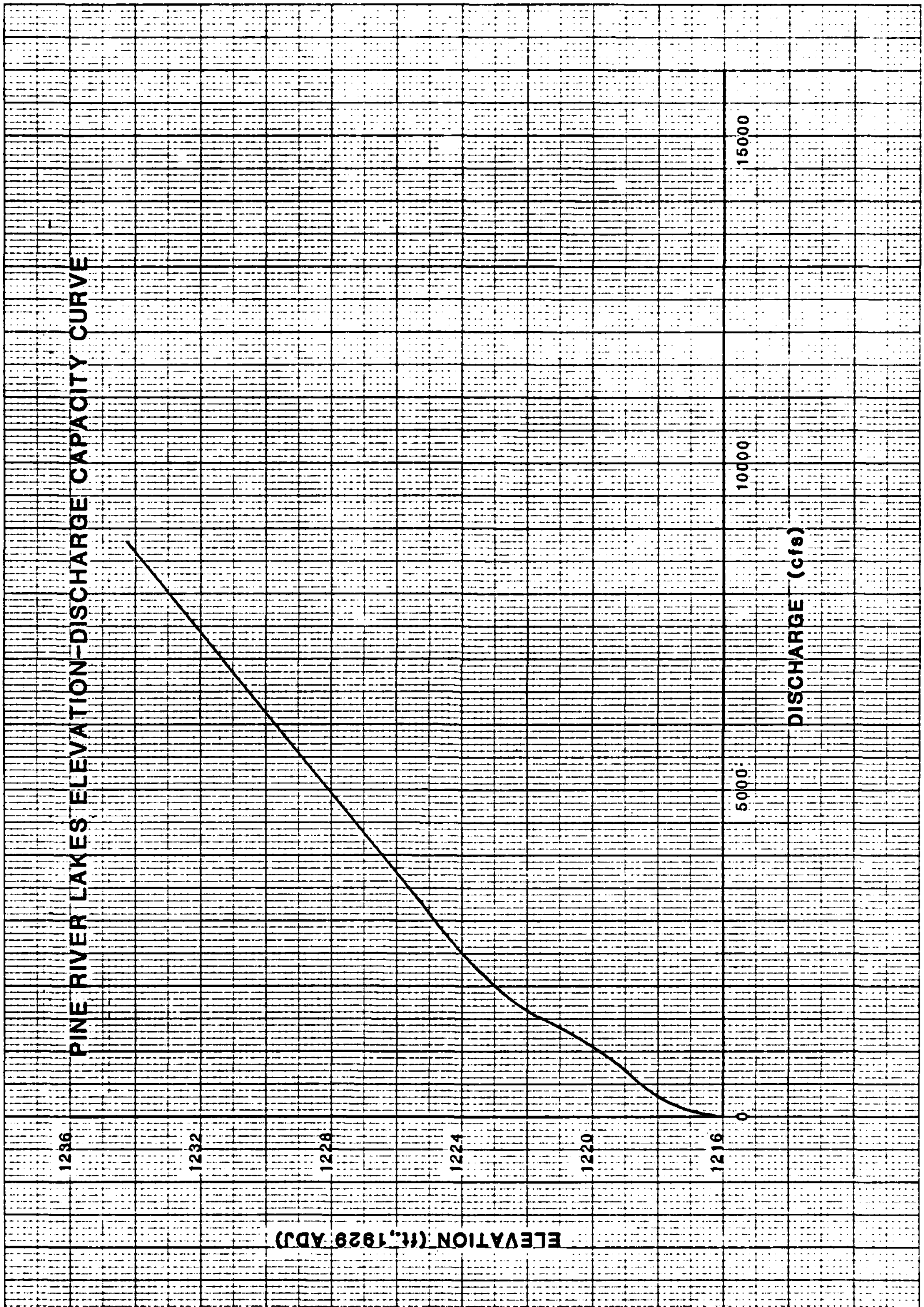

PINE RIVER LAKES ELEVATION-DISCHARGE CAPACITY CURVE
DISCHARGE (cfs)
0
5000
10000
15000
ELEVATION (ft., 1929 ADJ)
1216
1220
1224
1228
1232
1236

FIGURE 3-11

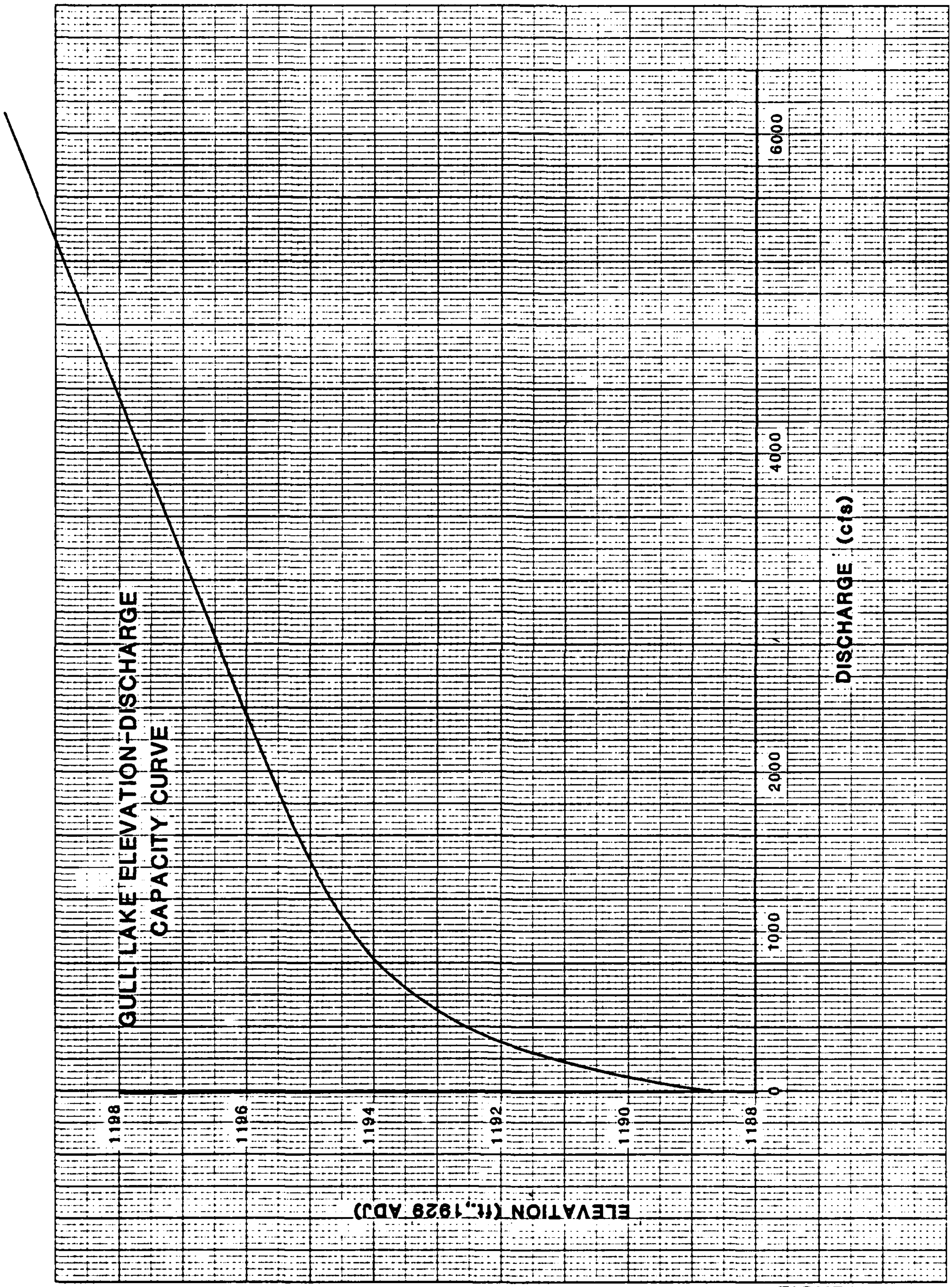

GULL LAKE ELEVATION-DISCHARGE
CAPACITY CURVE
DISCHARGE (cfs)
0
1000
2000
4000
6000
ELEVATION (ft, 1929 ADJ)
1188
1190
1192
1194
1196
1198

FIGURE 3-12

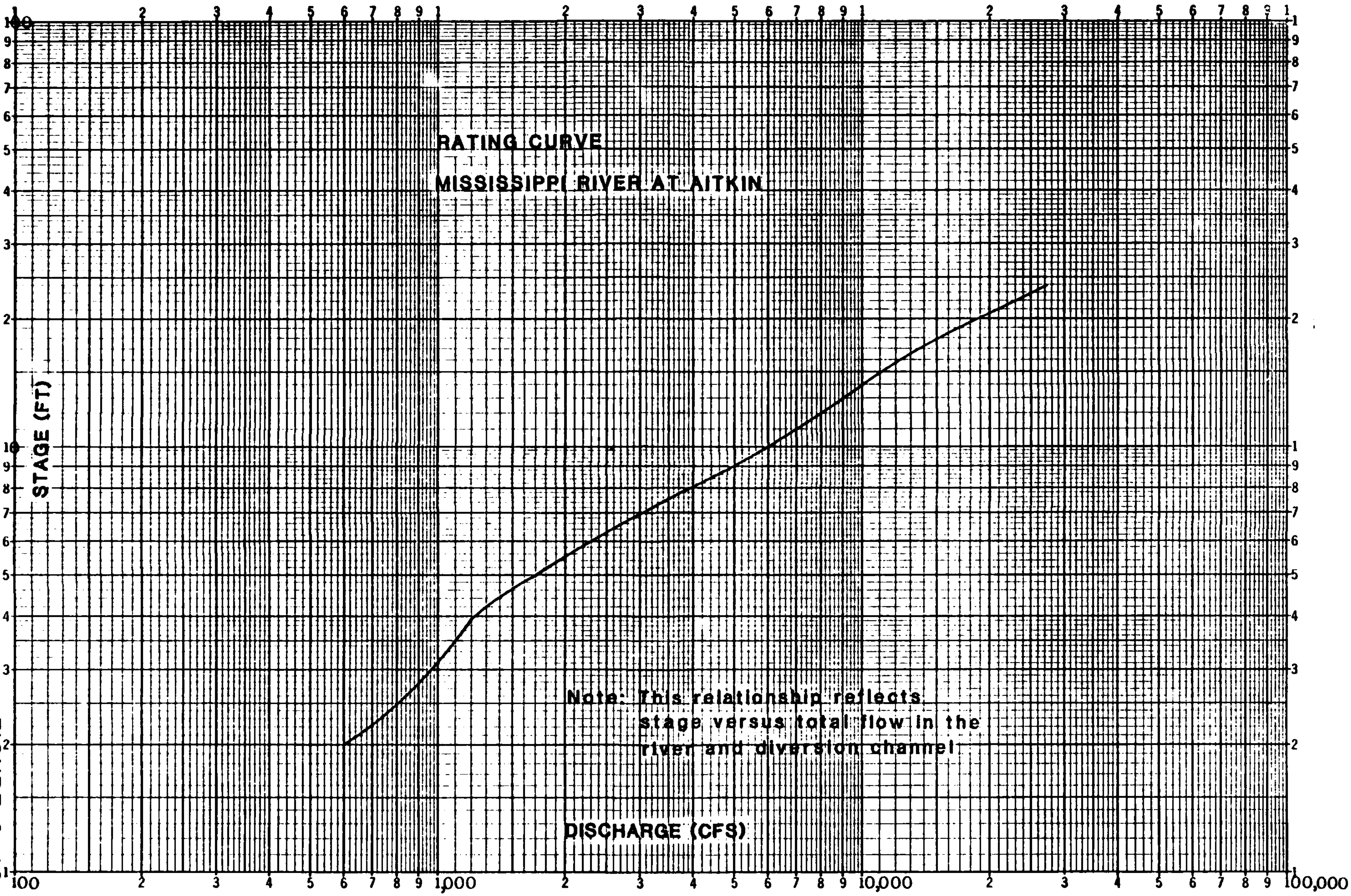

RATING CURVE
MISSISSIPPI RIVER AT AITKIN
STAGE (FT)
Note: This relationship reflects stage versus total flow in the river and diversion channel
DISCHARGE (CFS)
100
1,000
10,000
100,000

FIGURE 3-13

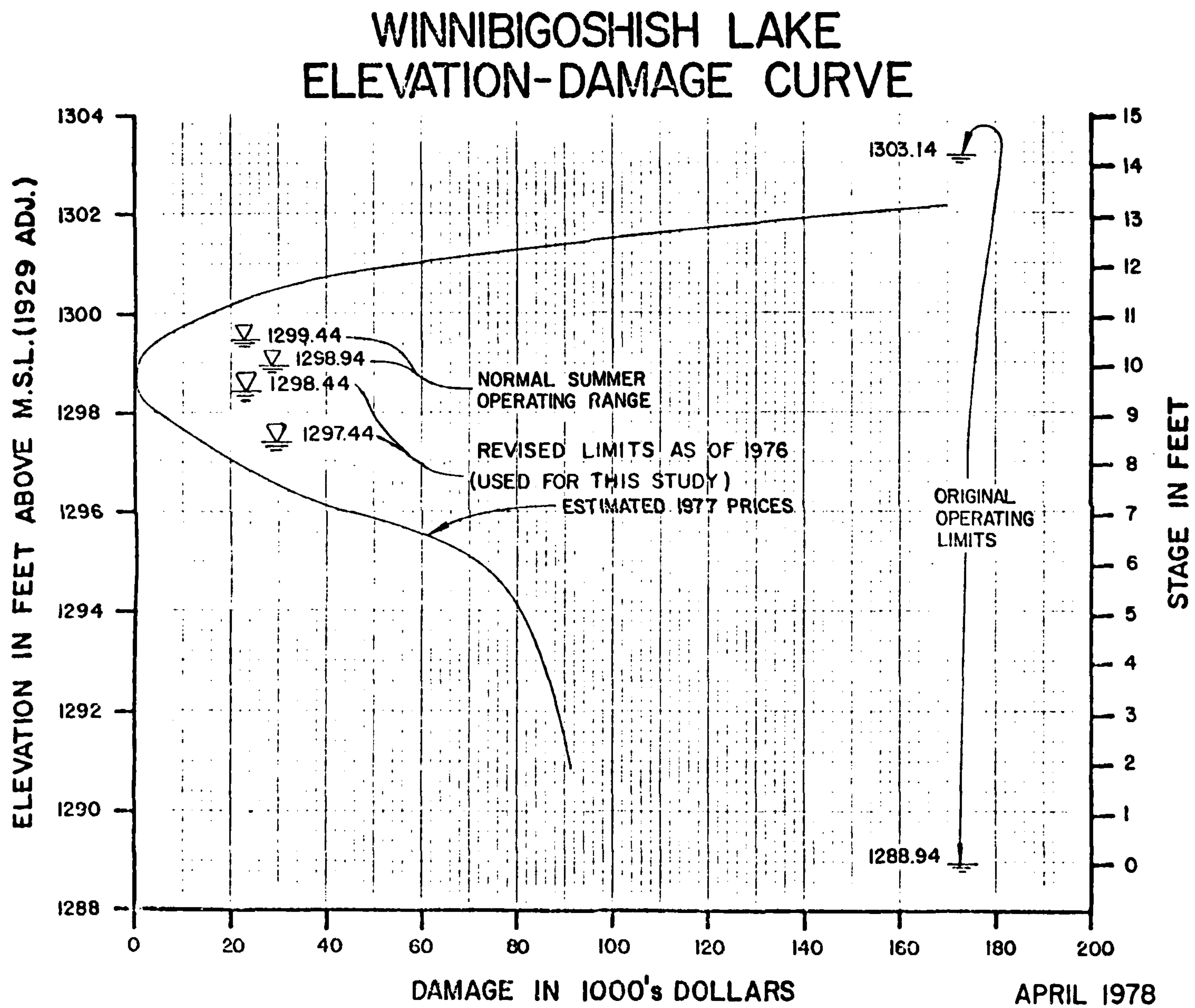
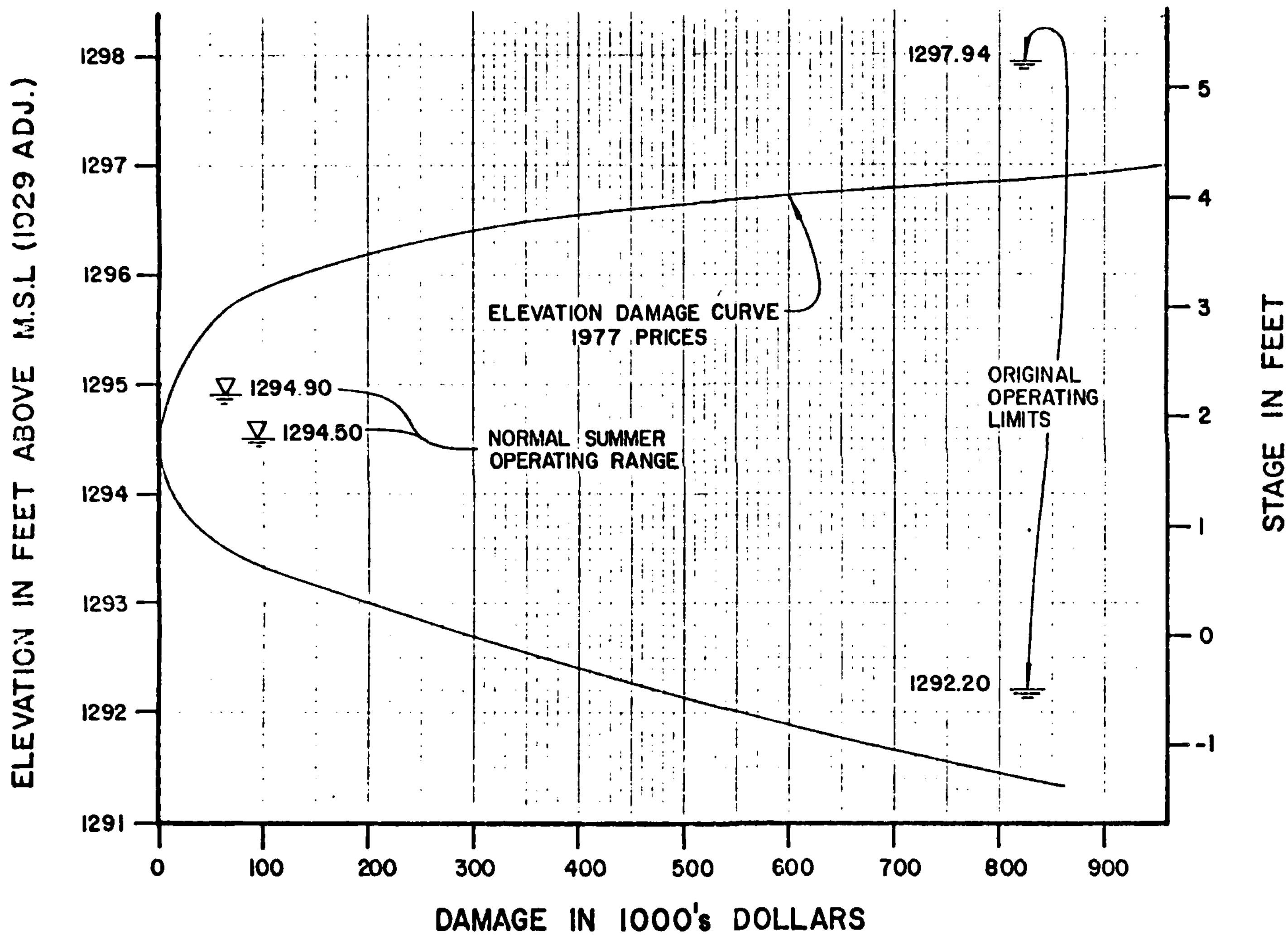

WINNIBIGOSHISH LAKE
ELEVATION-DAMAGE CURVE
ELEVATION IN FEET ABOVE M.S.L.(1929 ADJ.)
1304
1302
1300
1298
1296
1294
1292
1290
1288
1299.44
1298.94
1298.44
1297.44
NORMAL SUMMER
OPERATING RANGE
REVISED LIMITS AS OF 1976
(USED FOR THIS STUDY)
ESTIMATED 1977 PRICES
1303.14
1288.94
ORIGINAL
OPERATING
LIMITS
STAGE IN FEET
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
180
200
DAMAGE IN 1000's DOLLARS
APRIL 1978

FIGURE 3-14

LEECH LAKE
ELEVATION-DAMAGE CURVE



APRIL 1978

FIGURE 3-15

POKEGAMA LAKE
ELEVATION-DAMAGE CURVE

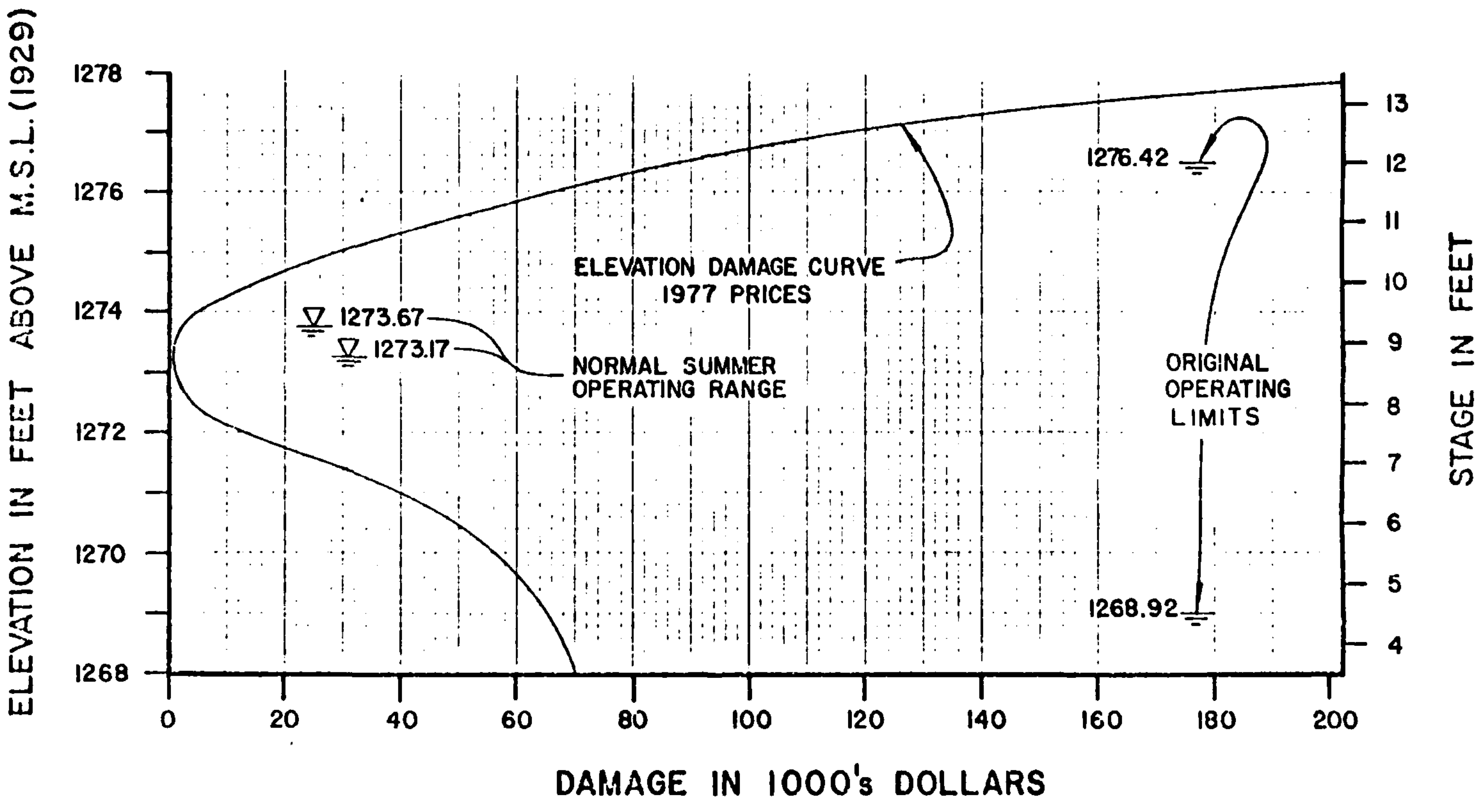
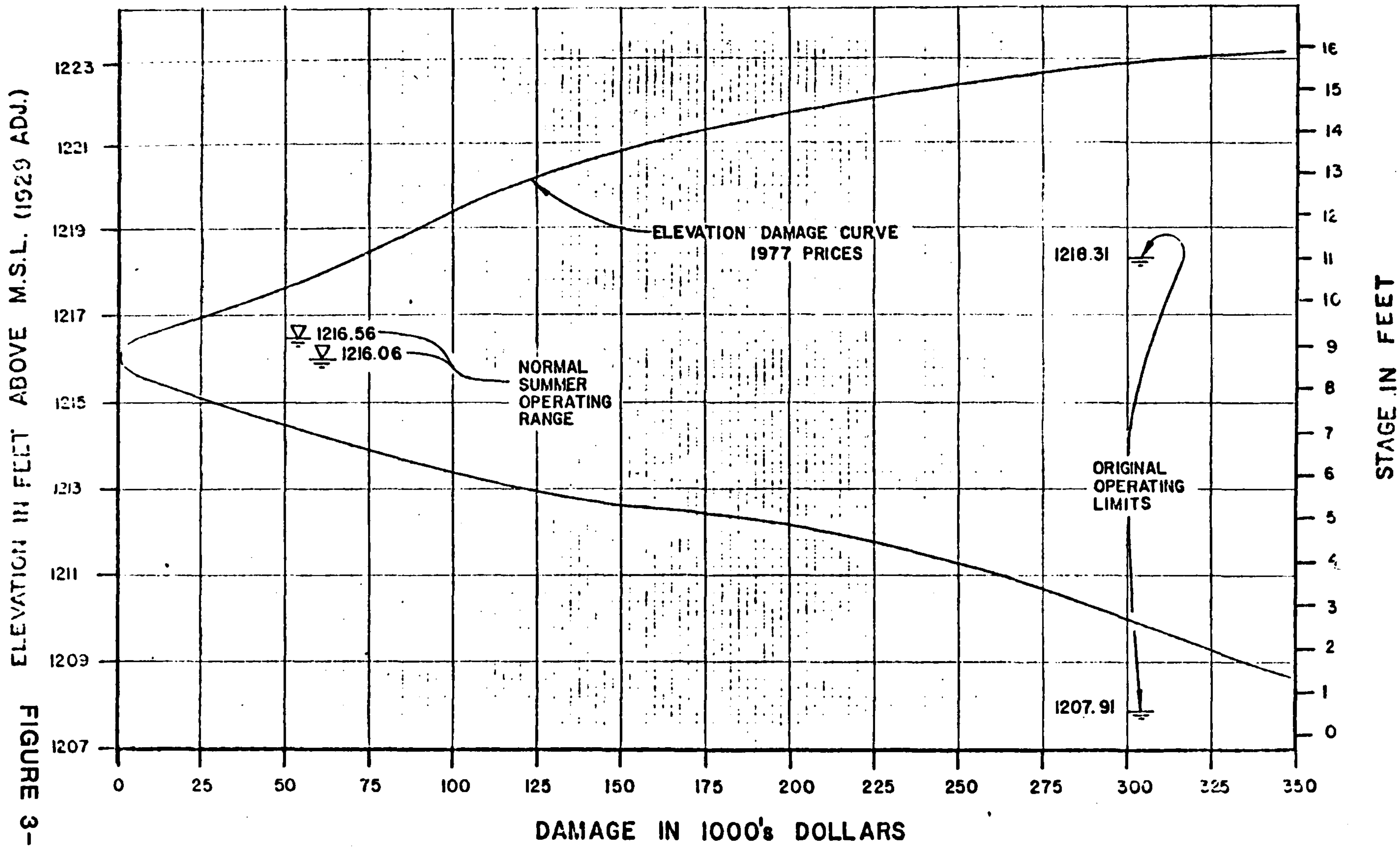


FIGURE 3-16

APRIL 1978

SANDY LAKE
ELEVATION-DAMAGE CURVE



APRIL 1978

FIGURE 3-17

PINE LAKE
ELEVATION-DAMAGE CURVE

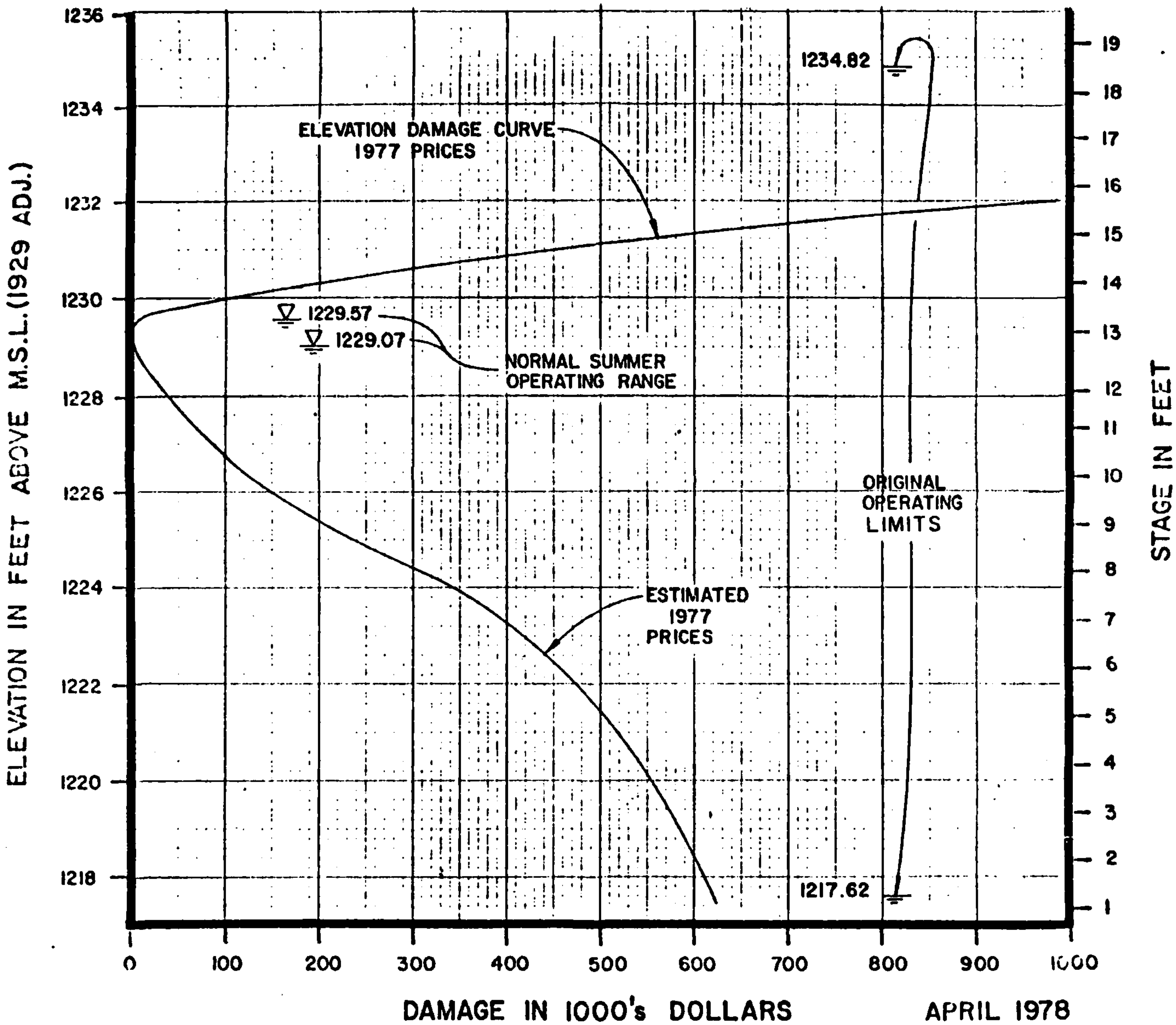
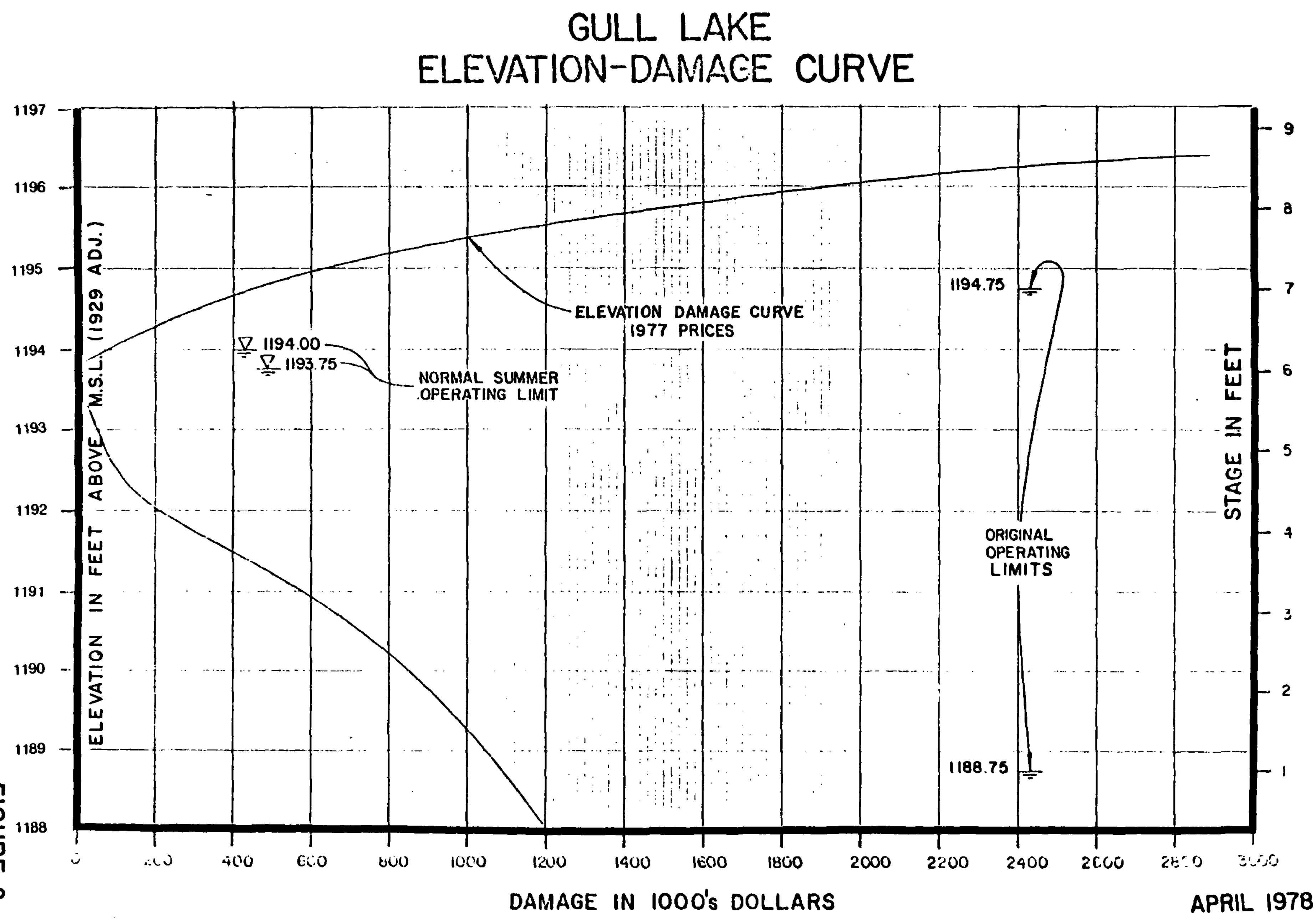


FIGURE 3-18



APRIL 1978

FIGURE 3-19

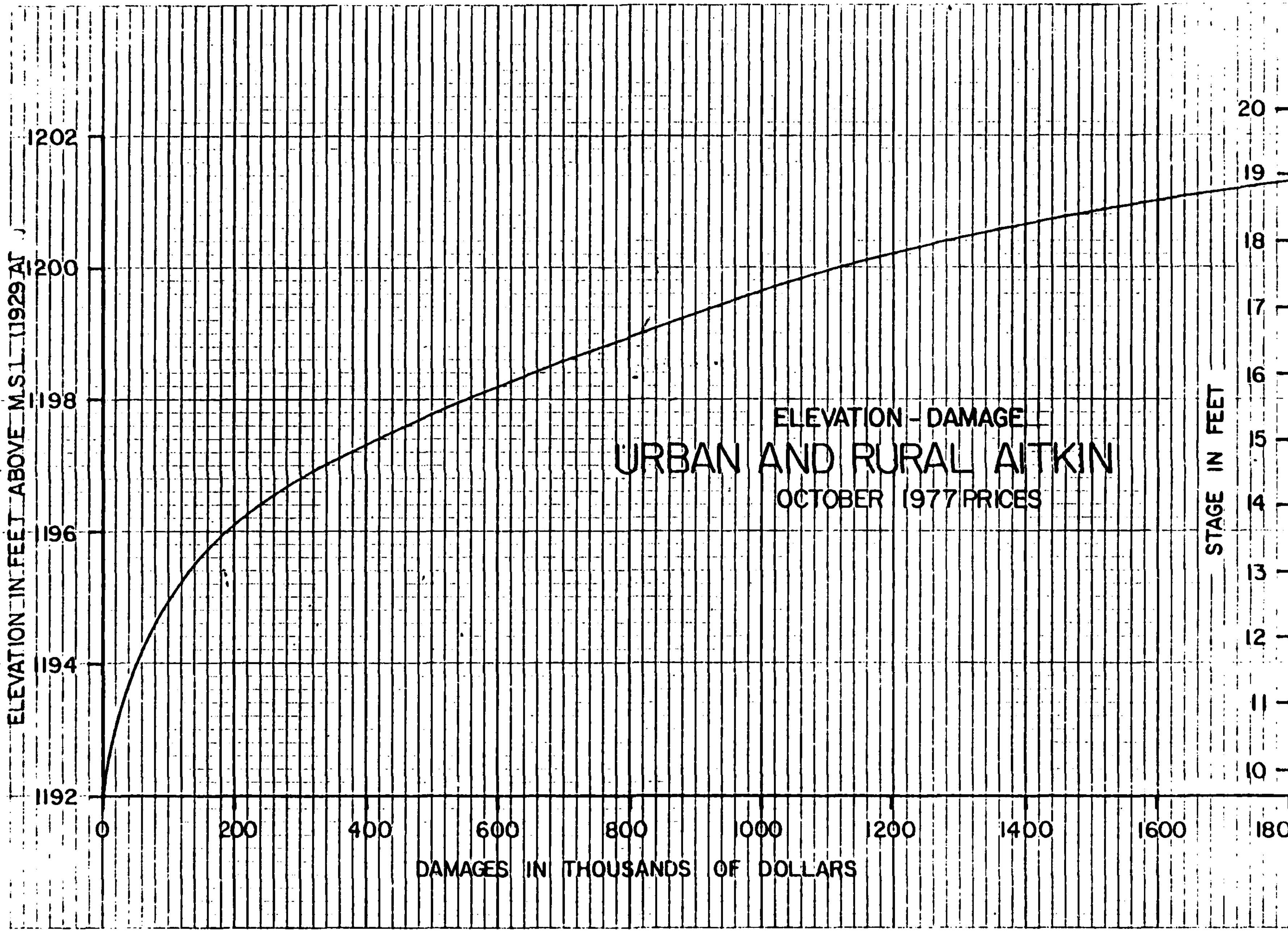

ELEVATION - DAMAGE
URBAN AND RURAL AITKIN
OCTOBER 1977 PRICES
ELEVATION IN FEET ABOVE M.S.L. (1929 AT.)
1202
1200
1198
1196
1194
1192
STAGE IN FEET
20
19
18
17
16
15
14
13
12
11
10
0
200
400
600
800
1000
1200
1400
1600
1800
DAMAGES IN THOUSANDS OF DOLLARS

FIGURE 3-20

SECTION 4

PLAN 1 - PRESENT OPERATING PLAN

OBJECTIVE

This plan simulates, as closely as possible, the current reservoir operation rules used by the St. Paul District. The hydrologic and economic results form the baseline upon which other plans are measured.

DISCUSSION

This is a reevaluation of the work performed by SAFHL and conforms to the description provided in their final report (Reference 1, pp. 36-45). Although computer simulation can duplicate operations in most respects, there are certain criteria which cannot be exactly duplicated as identified in the SAFHL report (Pokegama-Sandy-Aitkin rule curve, plan modification based upon long-range spring melt predictions and backwater effects). The HEC-5 simulation does approximate these effects so that the results are within the overall accuracy range of the basic data elements. Simulation results are a good measure of relative difference between plans since all plans experience the same simulation limitations.

The Present Operating Plan follows the reservoir index level criteria specified in Figures 4-1 through 4-6. A similar representation is provided for all plans in following sections of this report. The basic reservoir operating procedure is to draw reservoirs down to lower levels during the fall and let them rise to summer target levels during the late spring. This process is simulated using index Levels 3 and 4 as shown on these figures.

RESULTS

Since the simulation was initiated in 1930, the reservoir storage levels in January 1932 differ from the initial storage values assumed by SAFHL. As a result, the simulated values in this study differ from SAFHL results during the early 1930's but quickly converge and approximate the SAFHL results thereafter. There are some differences due to slightly revised specifications at the reservoirs and a revised damage curve for Aitkin. These revised specifications include lowering Winnibigoshish Reservoir summer operating limits by one foot (see Figure 3-14) and updating the elevation-discharge capacity curves for the six reservoirs (Figures 3-7 through 3-12).

Hydraulic Results

The hydraulic results for each plan are extensive. Details can be found in the HEC-5 computer output (provided on computer tape) for both monthly flow and daily flow simulations. This output displays the following information for each time period in the simulation:

For each reservoir -

- inflow
- outflow
- end-of-period storage
- level (index level)
- elevation
- case (criteria for reservoir release)

For Aitkin -

- channel capacity
- regulated flow
- cumulative local flow (from all nonreservoir drainage areas)
- change (flow contribution from reservoirs)
- elevation

For Anoka -

- regulated flow
- cumulative local flow
- change
- minimum required flow
- shortage (only meaningful for low flow plans)

For Libby, Royalton, and St. Paul -

- regulated flow
- cumulative local flows

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin, and annual minimum flow at Anoka is provided in tables in Appendix E. A plot of reservoir elevation versus time is also included in Appendix E for each reservoir along with streamflow at Aitkin and Anoka. This information represents the revised monthly time series values (combination of monthly and daily simulation results).

Frequency Results

Frequency relationships based upon the 47 years of simulated record are provided on Figures 4-7 through 4-14 for high stage at reservoirs, low stage at reservoirs, high flow at Aitkin, and low flow at Anoka. Note that the high stage and low stage curves cross with the high stage curve always sloping down from right to left (low frequency to high frequency) and the low stage curve sloping upward from right to left.

At times, the curves are horizontal for a range of frequencies. This is the result of the high or low stage reaching a constant value for a large number of years. This constant stage value usually (but not always) occurs at an index level stage. High stage values are controlled by the HEC-5 reservoir operation policy to not exceed Level 4, except in peak flood periods when stage values may rise to Level 5. Stage values rarely exceed Level 5 for any of the reservoirs (only Sandy Reservoir was simulated by HEC-5 to exceed the Level 5 stage) because of HEC-5 policy of producing surcharge routing to maximum outlet capacity to draw down the reservoir stage to Level 5 when it went above this index level. Horizontal low stage lines occur less frequently than for high stages and are found at two general levels. Low stage non-exceedance frequency results in the range of 80 to 99 percent occur often at index Level 4. These results are for the peak flood years when the minimum reservoir stage does not drop below Level 4 for the seasonal period of May through September. The second general occurrence of constant low stage values (horizontal frequency line) is found between Levels 2 and 3. These constant stage values are a result of the HEC-5 monthly simulation results when the program calculates an average stage value for the month. The lowest low stage values are often found in May when they are the average of the end of April and the end of May. April low stages are usually lower than May and correspondingly influence the low stage frequency results, although they are outside the target period of May through September. This effect on the frequency results was due to the elevation/stage averaging procedure in HEC-5.

The frequency results at the extremes of the curves are extrapolated from the Weibull plotting positions produced by the FATSO program. When necessary, the program extrapolates the plotting positions past the observed

data to extend the frequency results to the 0.2 precent probability level. This has been done for each reservoir for each plan.

The Weibull plotting positions produced by FATSO were not always used to draw the frequency curves at the extreme probabilities. Judgement was used at the extremes of the curves (90 to 99 percent and 10 to 0.2 percent levels) to determine the expected elevation for the appropriate frequency. These revised frequency results were then used in the EAD program to calculate the average annual damage for each reservoir.

The frequency curves were revised for two reasons. Extrapolation of the curves to the extreme frequency values by FATSO used the two most extreme Weibull plotting positions at each end of the curves. In some cases this results in frequency curves with unrealistically high or low reservoir elevations. Each curve was reviewed to determine if revision of the curve at the extreme ends was necessary.

Two examples are shown where the frequency curves were revised because of unrealistically high elevation values for the high stage curve. Figure 4-7 shows the actual Weibull plotting positions for Plan 1 high stage at Winnibigoshish. The highest reservoir elevation produced by HEC-5 at Winnibigoshish is at 1302.0 and occurred during the 1950 flood. This elevation is assigned a Weibull probability of 2.08, based on 47 years of HEC-5 data. This plotting position is very probably in error when considering a longer period of record and, in fact, is much more likely to be the highest elevation for a longer return period. If this is true, then the curve should be revised by decreasing the upward slope of the high stage curve at the low exceedance frequency. This was done in Figure 4-7 and for other frequency results where it was judged to better represent the expected frequency for extreme period events.

The second example of how the frequency curves were revised is shown in Figure 4-12. For this high stage curve the highest elevation during the 47-year period is 1194.8, which corresponds to Level 5. Extrapolation of the Weibull plotting points by the FATSO program to determine 1, 0.5, and 0.2 percent exceedance probabilities produces a rising straight line based on the actual elevations at 4.17 and 2.08 percent probability

This extrapolation to 0.2 percent probability has been revised based on the effect of the reservoir operation policy which attempts to release all excess water if the reservoir elevation rises above Level 5 (top of flood control pool). It is impossible to determine if and by how much the elevation may rise above Level 5 at 0.2 percent exceedance probability (once in 500 years). However, there is no evidence produced by HEC-5 to support raising the curve above Level 5 as it extends out to 0.2 percent probability. For this reason the curve was extended horizontally at the Level 5 elevation. This was done for the high stage curve in Figure 4-12 and for other high stage frequency results where appropriate.

Economic Results

Table 4-1 summarizes economic computations and compares this information to results produced by SAFHL (see Reference 1, pg. 149). It should be noted that average annual cost at Anoka represents the cost associated with not meeting the 1,600 cfs requirement. This is not truly a cost since this plan is not directed towards supplying this requirement as is the case for Plan 2 - Low Flow, 1,600 cfs at Anoka. The Plan 1 value provides a base to measure improvement achieved by Plan 2 and other plans.

The comparison of this study's Plan 1 results and those produced by SAFHL shows some major differences in the amount of average annual damage for the reservoirs and at Aitkin and Anoka. These differences are the result of the following factors:

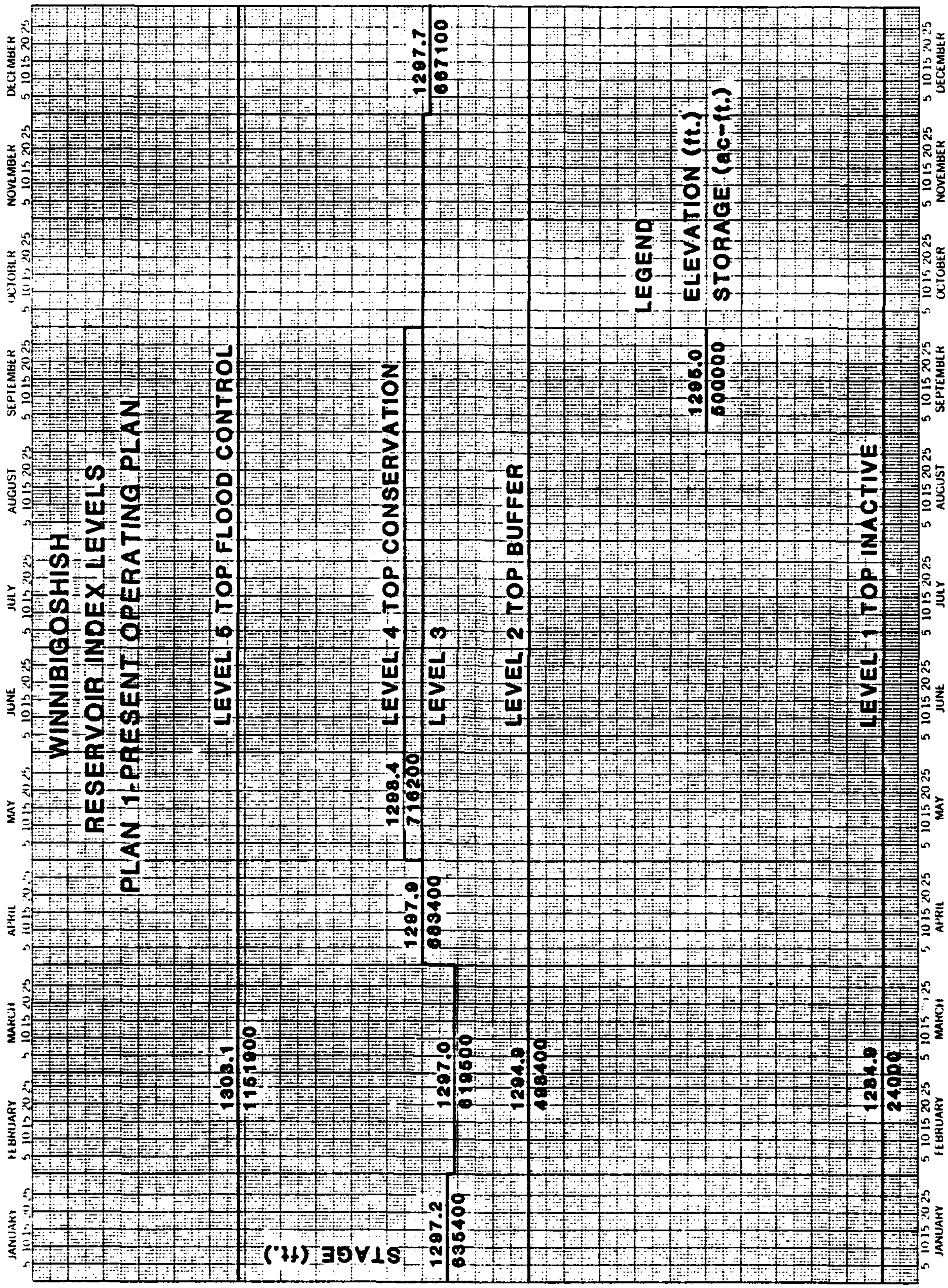
(1) changes to HEC-5,
(2) refinement of the elevation-damage curves, and
(3) different procedures used to calculate average annual damage

These differences are not present when comparing the other plans' results with Plan 1 and for this reason all further comparisons will be made with the new Plan 1 results presented in Table 4-1.

TABLE 4-1

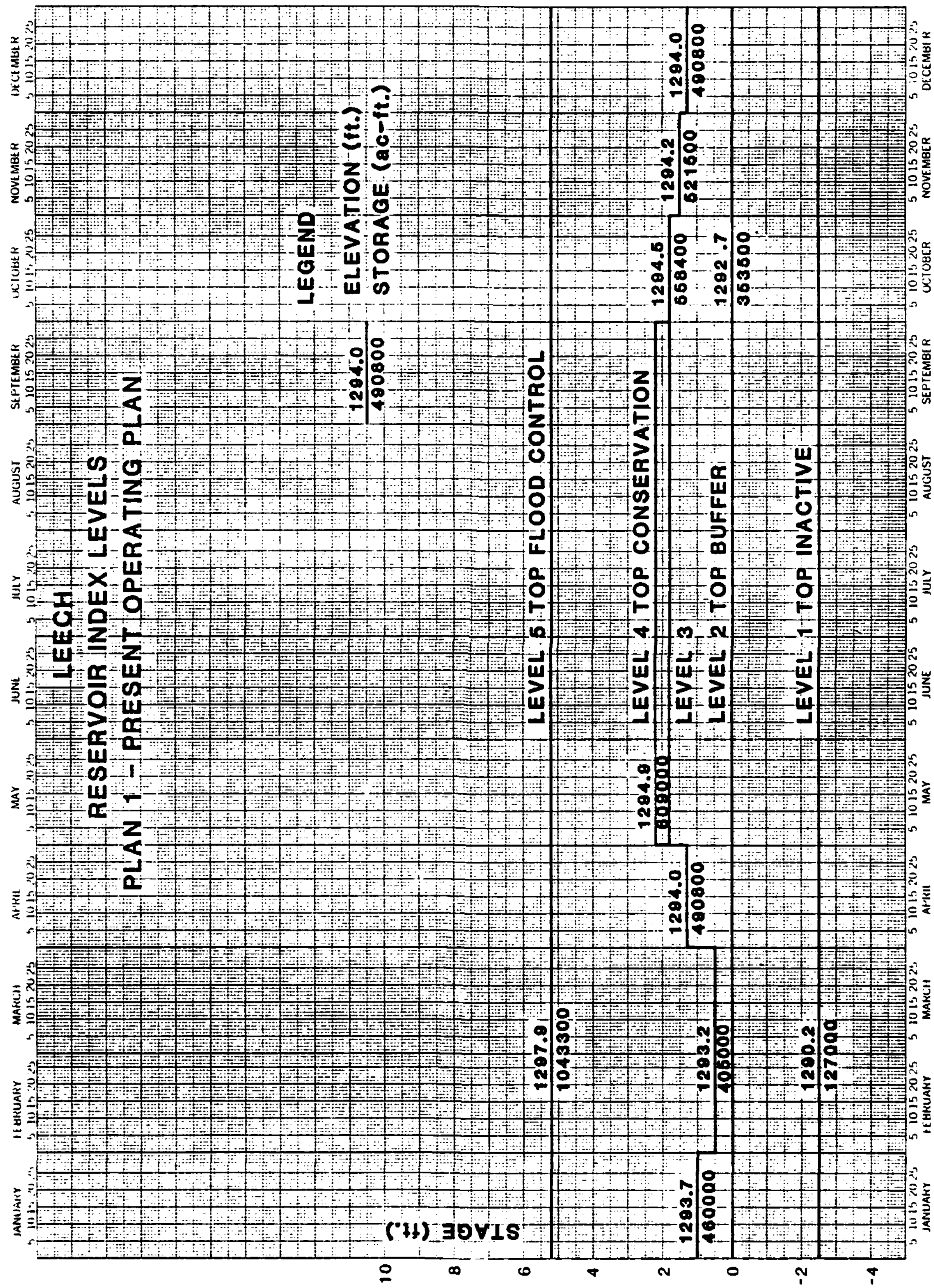
ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 1	SAFHL PLAN 1
Winnibigoshish		
High Stage	4.0	15.0
Low Stage	9.7	17.5
Total	13.7	32.5
Leech		
High Stage	11.0	16.8
Low Stage	71.3	79.3
Total	82.3	96.1
Pokegama		
High Stage	25.0	62.4
Low Stage	2.8	6.4
Total	27.8	68.8
Sandy		
High Stage	29.4	90.3
Low Stage	2.1	6.5
Total	31.5	96.8
Pine		
High Stage	16.6	16.6
Low Stage	6.3	16.8
Total	22.9	33.4
Gull		
High Stage	127.5	96.2
Low Stage	15.2	23.9
Total	142.7	120.1
Aitkin		
High Flow	278.6	309.6
TOTAL AAD	599.5	757.3
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	3,189.9	4,488.5



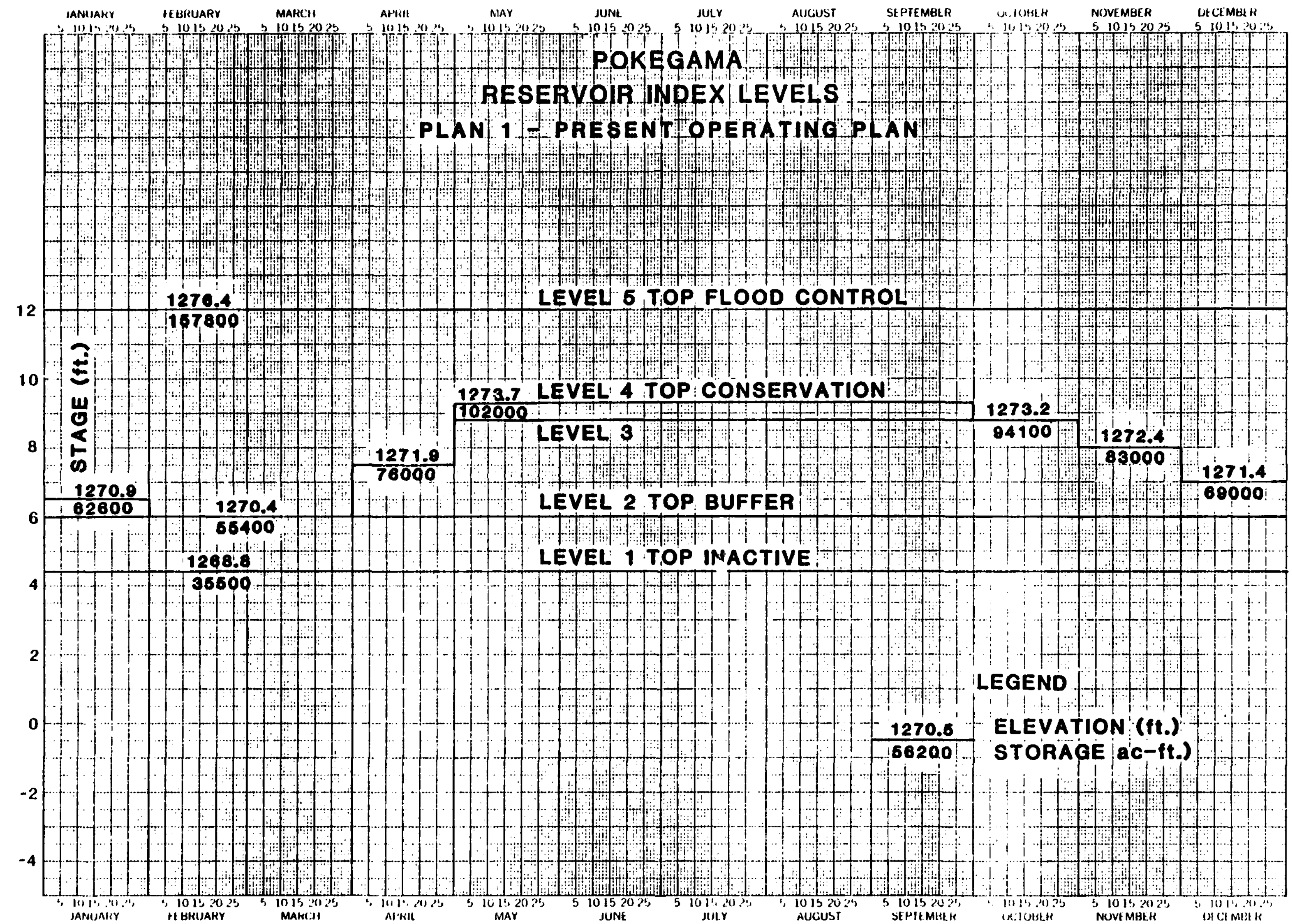
WINNIBIGOSHISH
RESERVOIR INDEX LEVELS
PLAN 1-PRESENT OPERATING PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
1303.1
1151900
1297.2
635400
1297.0
619500
1294.9
498400
1284.9
24000
1297.9
683400
1298.4
716200
1295.0
500000
1297.7
667100
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 4-1



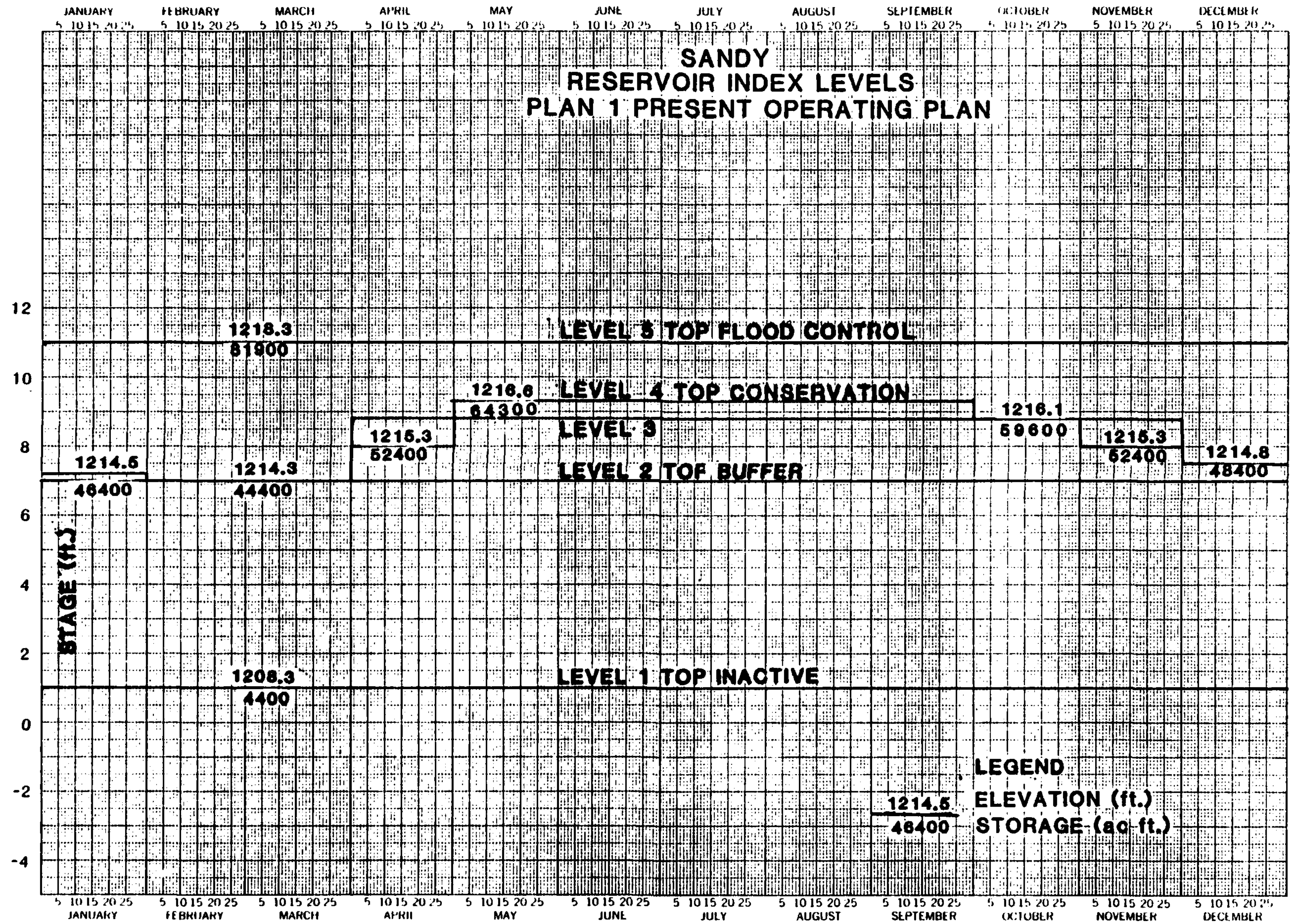
LEECH
RESERVOIR INDEX LEVELS
PLAN 1 - PRESENT OPERATING PLAN
LEGEND
1294.0
490800
ELEVATION (ft.)
STORAGE (ac-ft.)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1297.9
1043300
1293.7
460000
1293.2
405000
1294.0
490800
1294.9
609000
1294.5
558400
1294.2
621500
1294.0
490800
1292.7
353500
1290.2
127000
STAGE (ft.)
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 4-2



POKEGAMA
RESERVOIR INDEX LEVELS
PLAN 1 – PRESENT OPERATING PLAN
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
STAGE (ft.)
12
10
8
6
4
2
0
-2
-4
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1276.4
157800
1270.9
62600
1270.4
55400
1268.8
35500
1271.9
76000
1273.7
102000
1273.2
94100
1272.4
83000
1271.4
69000
1270.5
56200
LEGEND
ELEVATION (ft.)
STORAGE ac-ft.)

FIGURE 4-3



SANDY
RESERVOIR INDEX LEVELS
PLAN 1 PRESENT OPERATING PLAN
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
STAGE (ft.)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1218.3
81900
1216.6
64300
1216.1
59600
1215.3
52400
1215.3
52400
1214.5
46400
1214.3
44400
1214.8
48400
1208.3
4400
LEGEND
1214.5 ELEVATION (ft.)
46400 STORAGE (ac ft.)

FIGURE 4-4

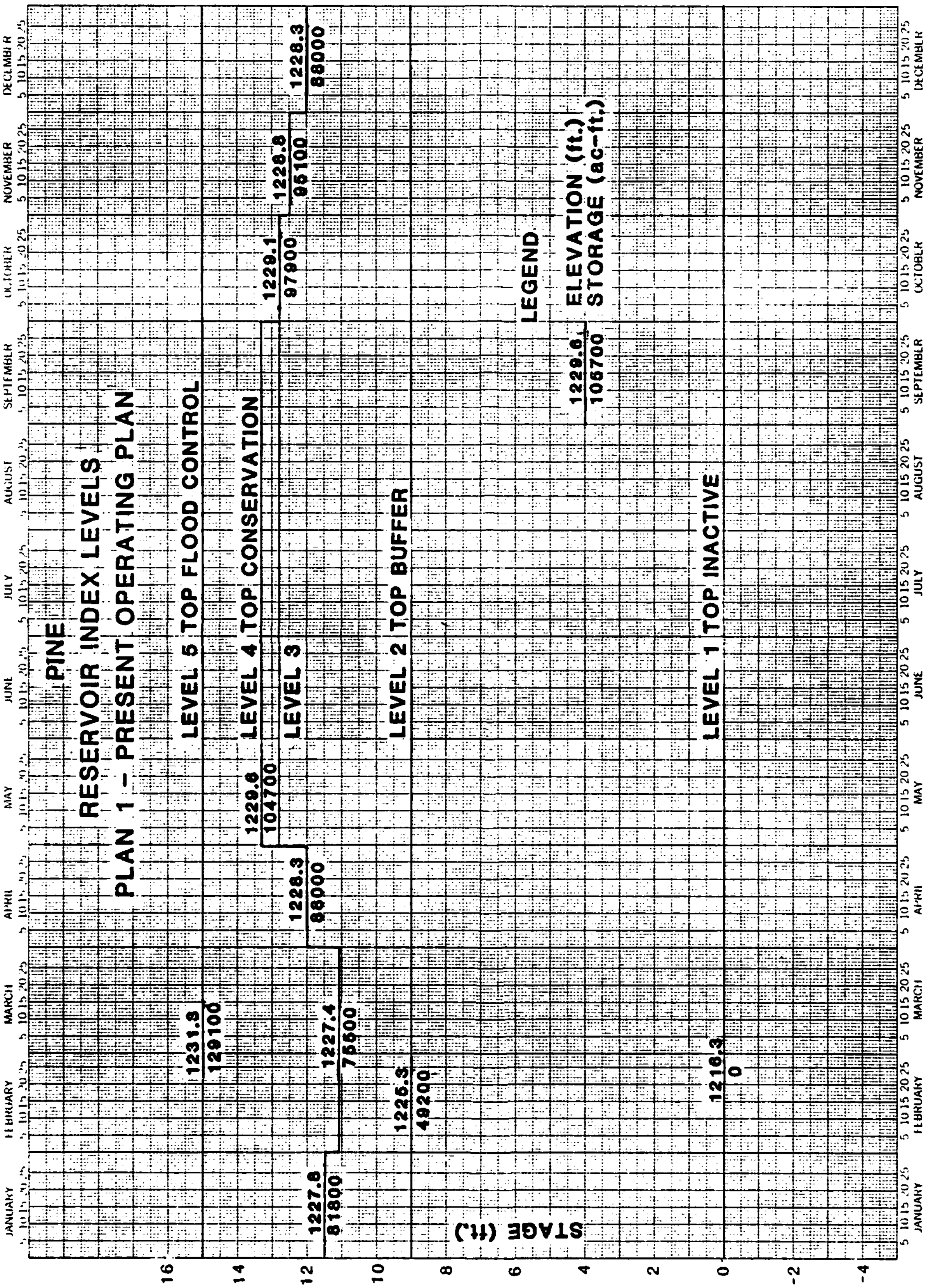

PINE
RESERVOIR INDEX LEVELS
PLAN 1 – PRESENT OPERATING PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
1229.6
105700
STAGE (ft.)
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
1227.8
81800
1231.3
129100
1227.4
75500
1225.3
49200
1216.3
0
1228.3
88000
1229.6
104700
1229.1
97900
1228.8
95100
1228.3
88000

FIGURE 4-5

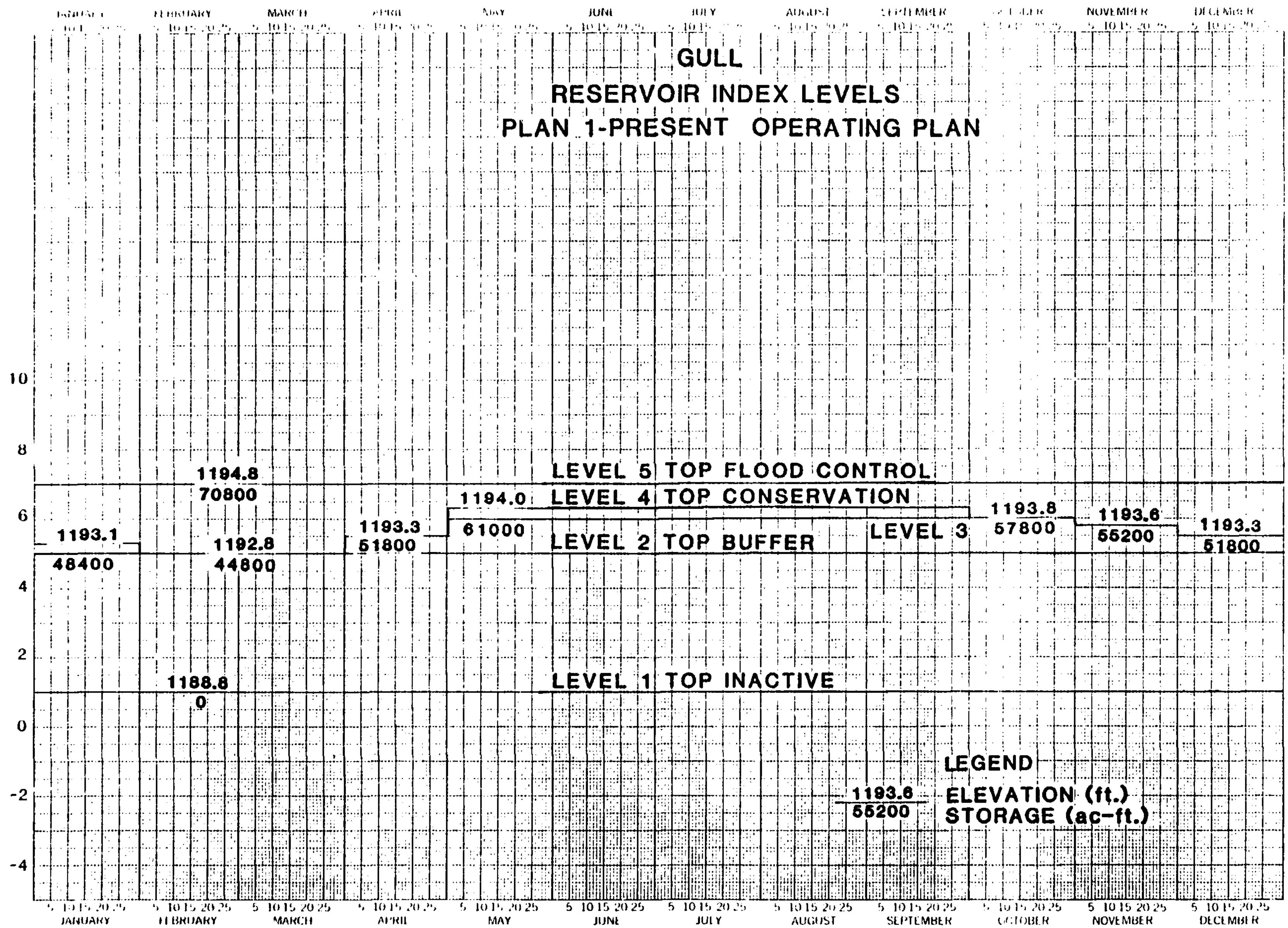

GULL
RESERVOIR INDEX LEVELS
PLAN 1-PRESENT OPERATING PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1194.8
70800
1193.1
48400
1192.8
44800
1188.8
0
1193.3
51800
1194.0
61000
1193.8
57800
1193.6
55200
1193.3
51800
LEGEND
1193.6 ELEVATION (ft.)
55200 STORAGE (ac-ft.)
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 4-6

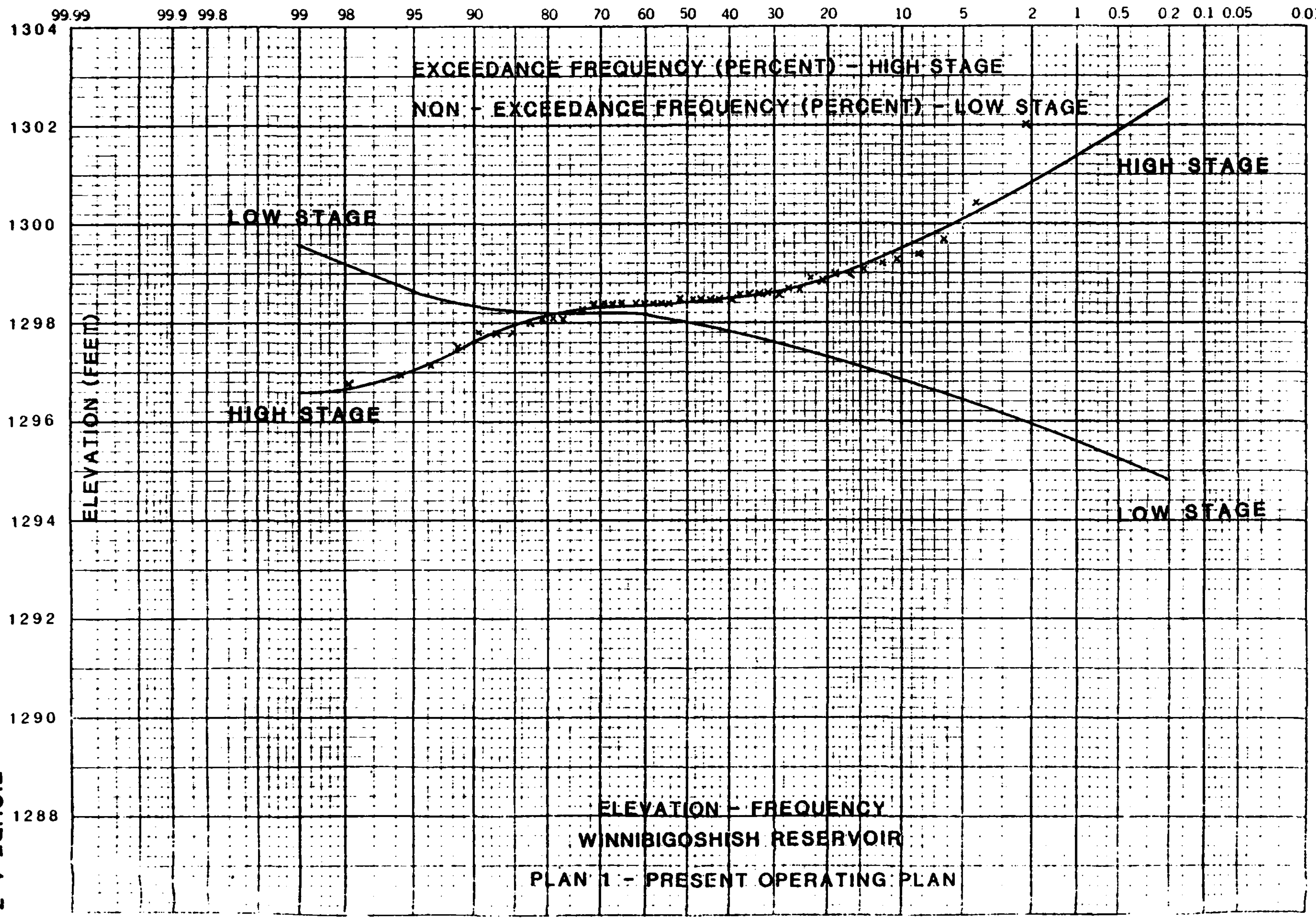
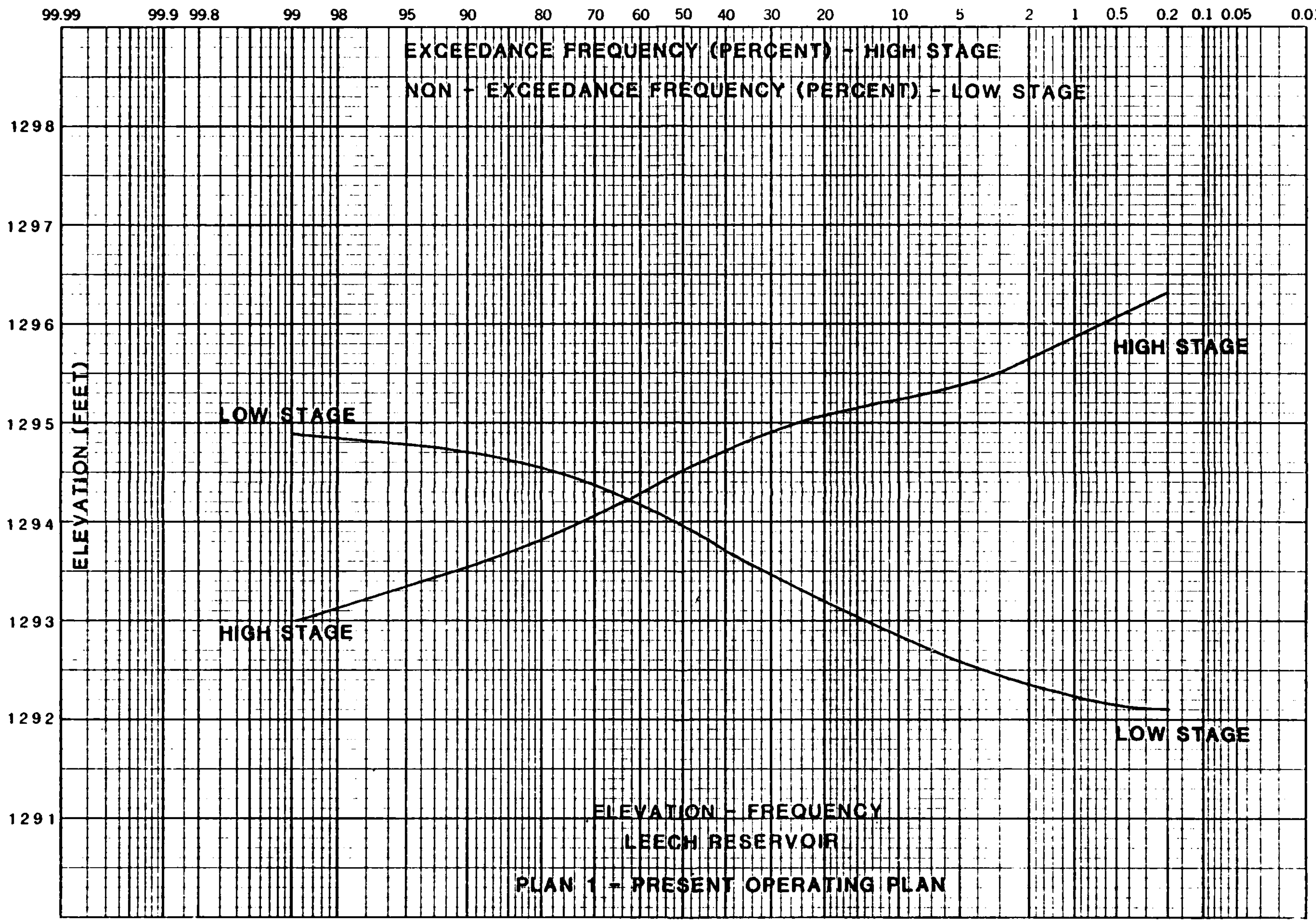

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION (FEET)
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
1304 1302 1300 1298 1296 1294 1292 1290 1288
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN

FIGURE 4-7



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
ELEVATION (FEET)
1298
1297
1296
1295
1294
1293
1292
1291
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN

FIGURE 4-8

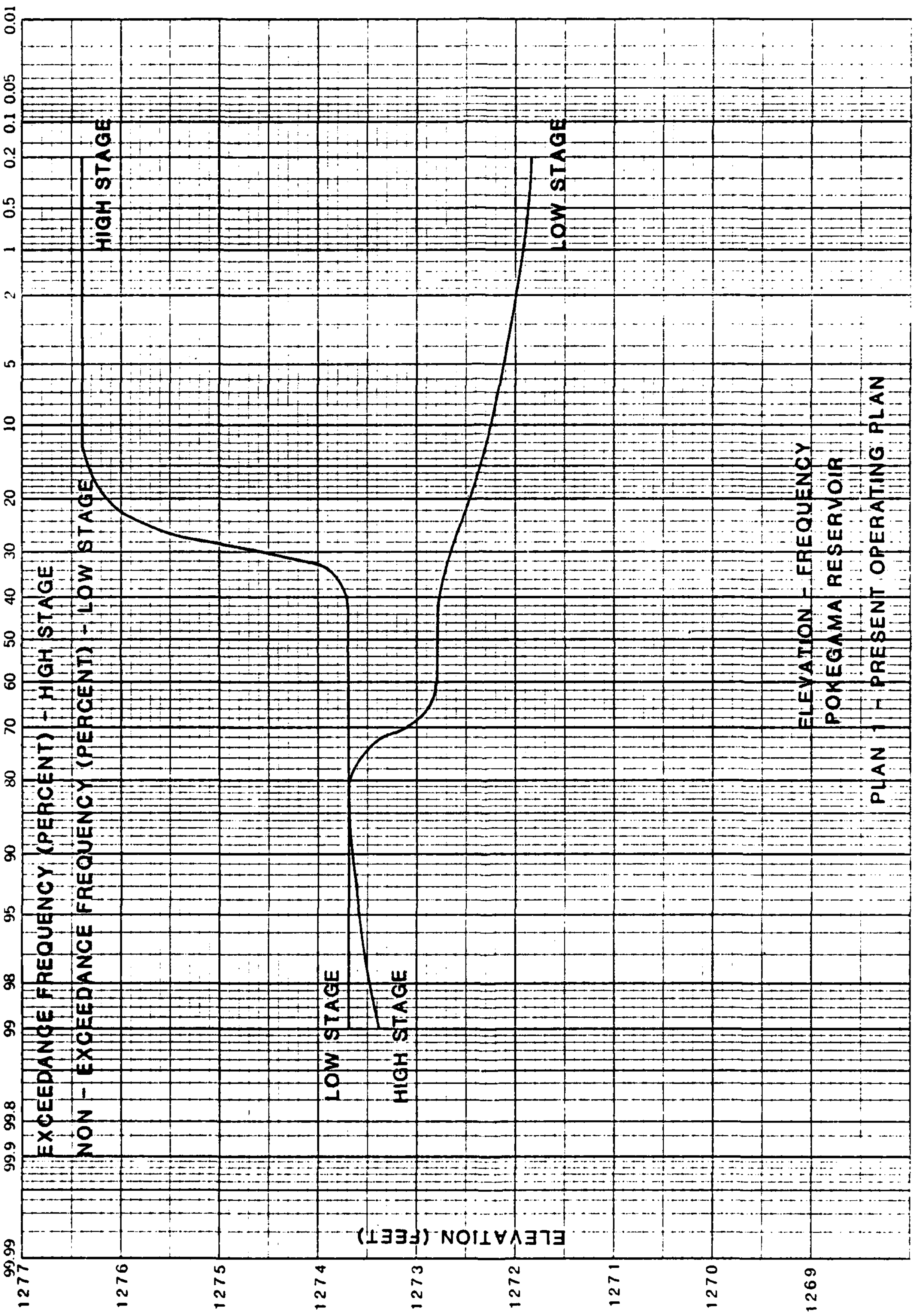

ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1277
1276
1275
1274
1273
1272
1271
1270
1269

FIGURE 4-9

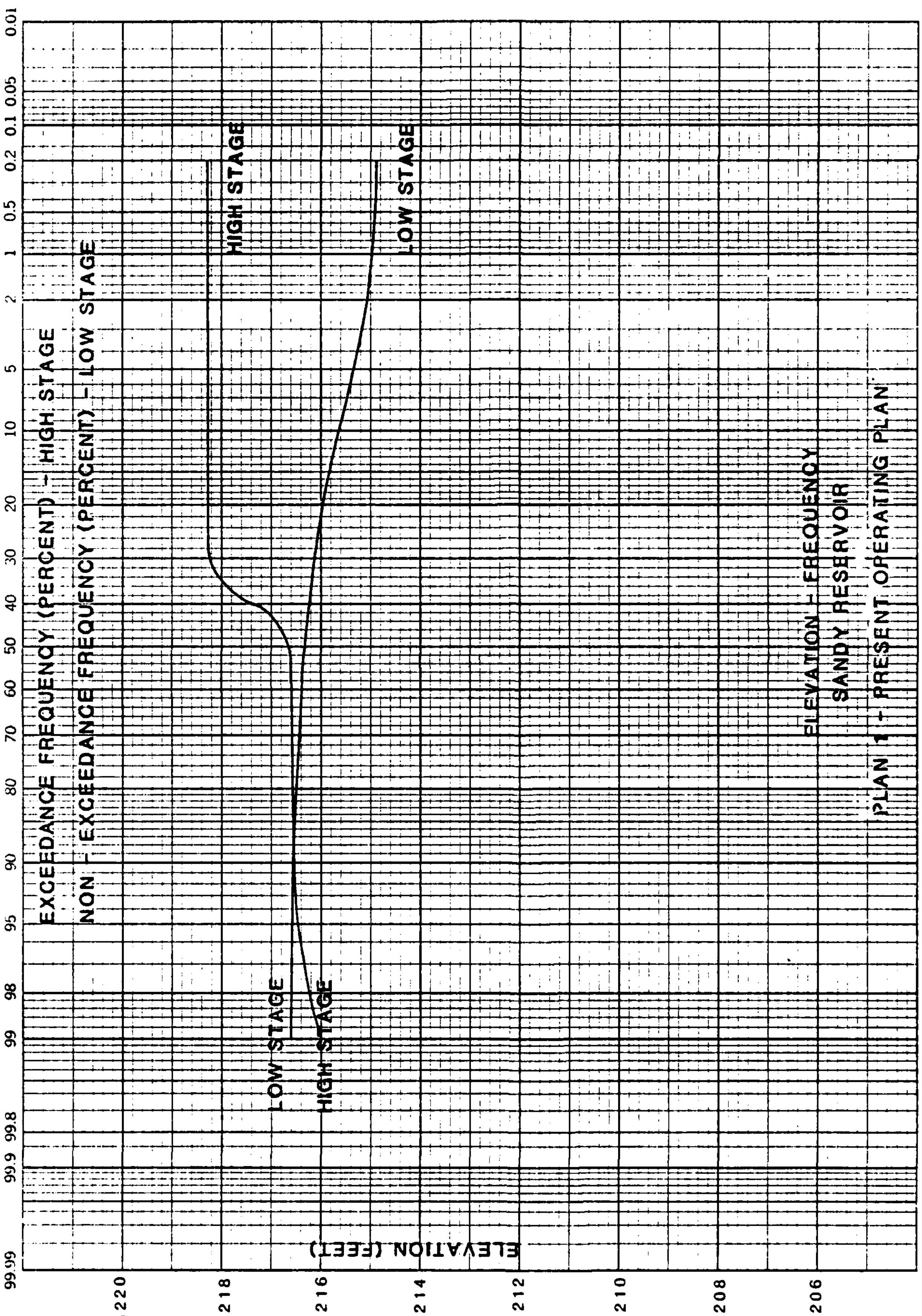
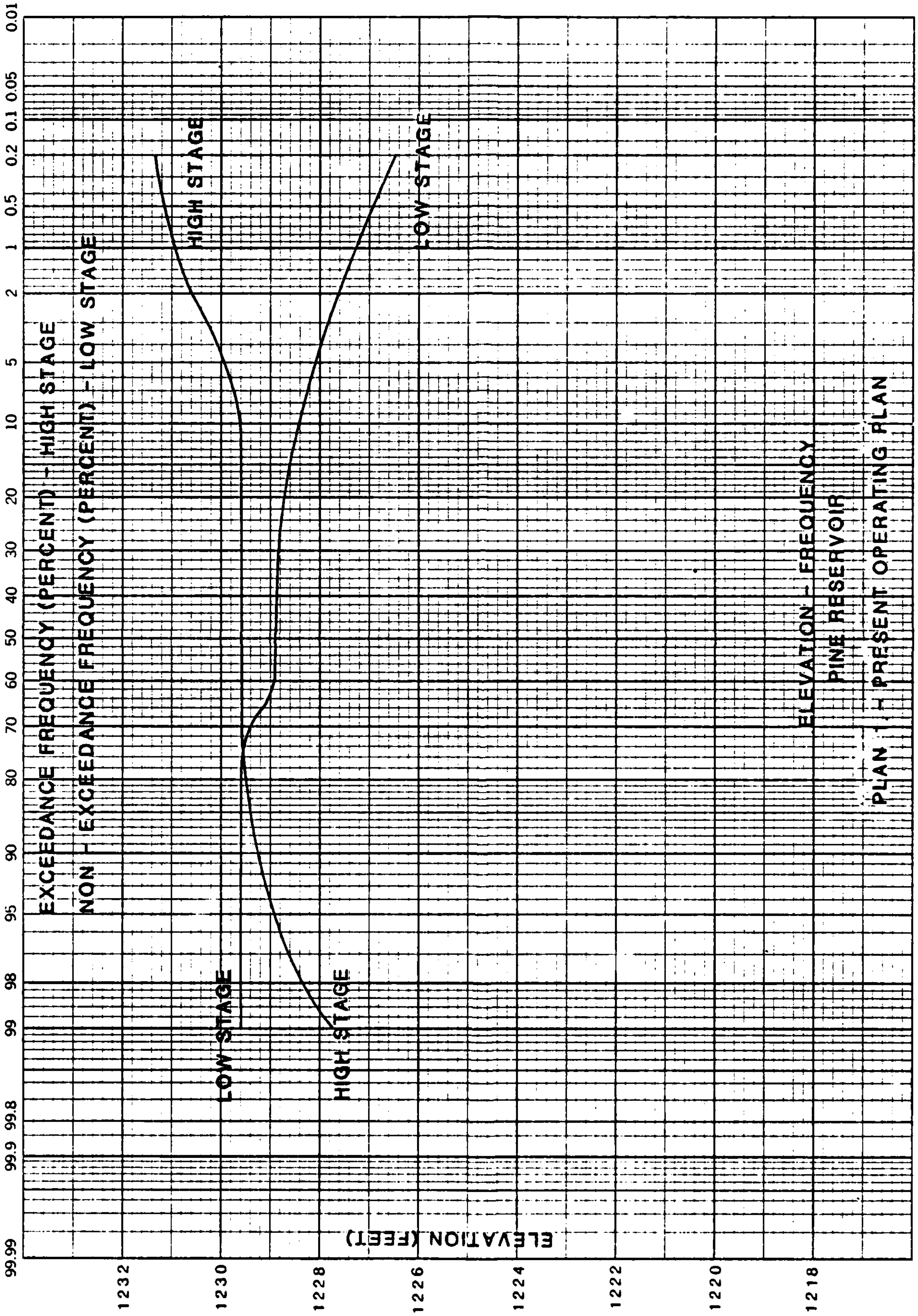

ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION (FEET)
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
1220 1218 1216 1214 1212 1210 1208 1206

FIGURE 4-10



ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN - H PRESENT OPERATING PLAN
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION (FEET)
1232
1230
1228
1226
1224
1222
1220
1218

FIGURE 4-11

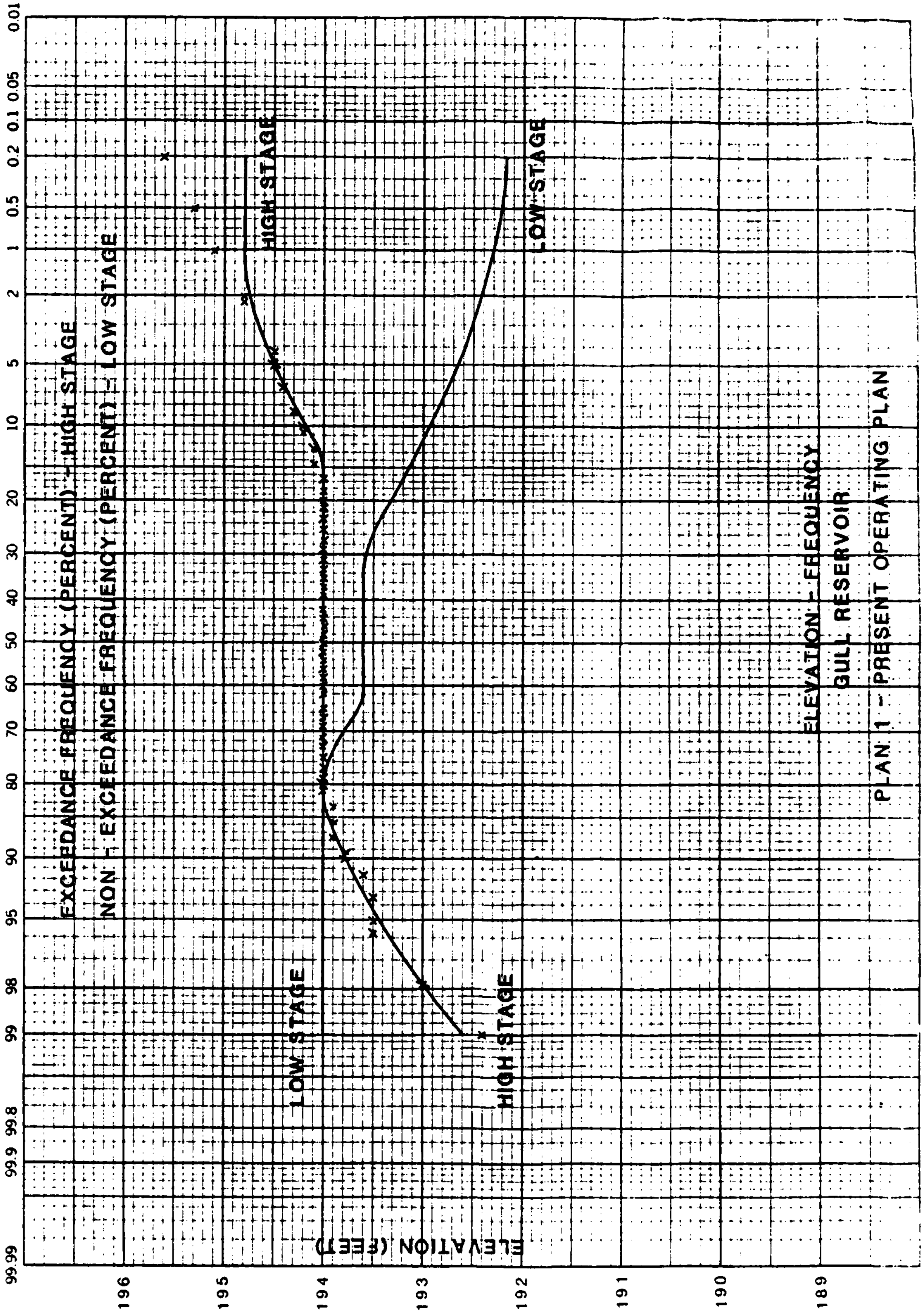

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION (FEET)
1196
1195
1194
1193
1192
1191
1190
1189
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN

FIGURE 4-12

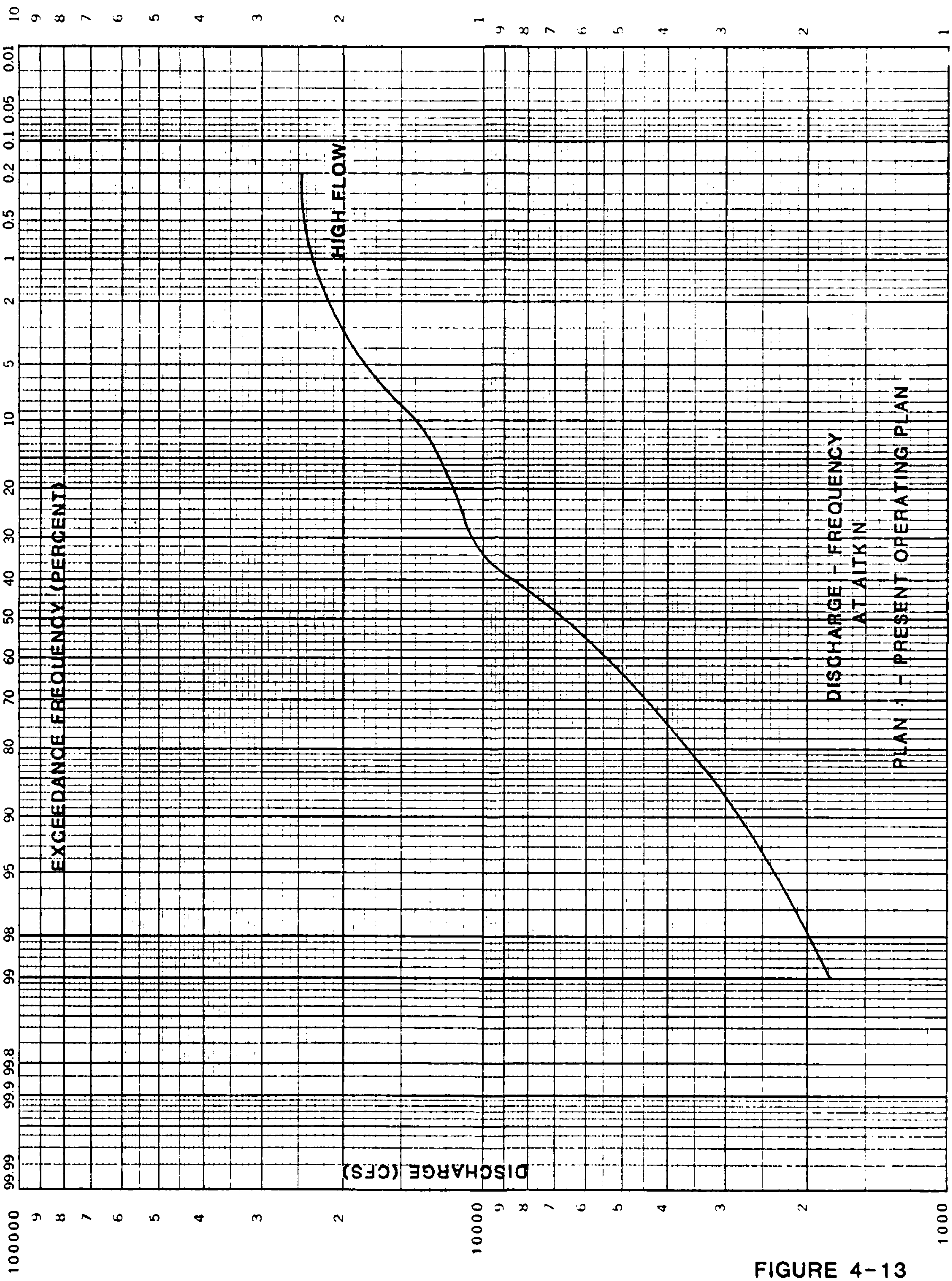
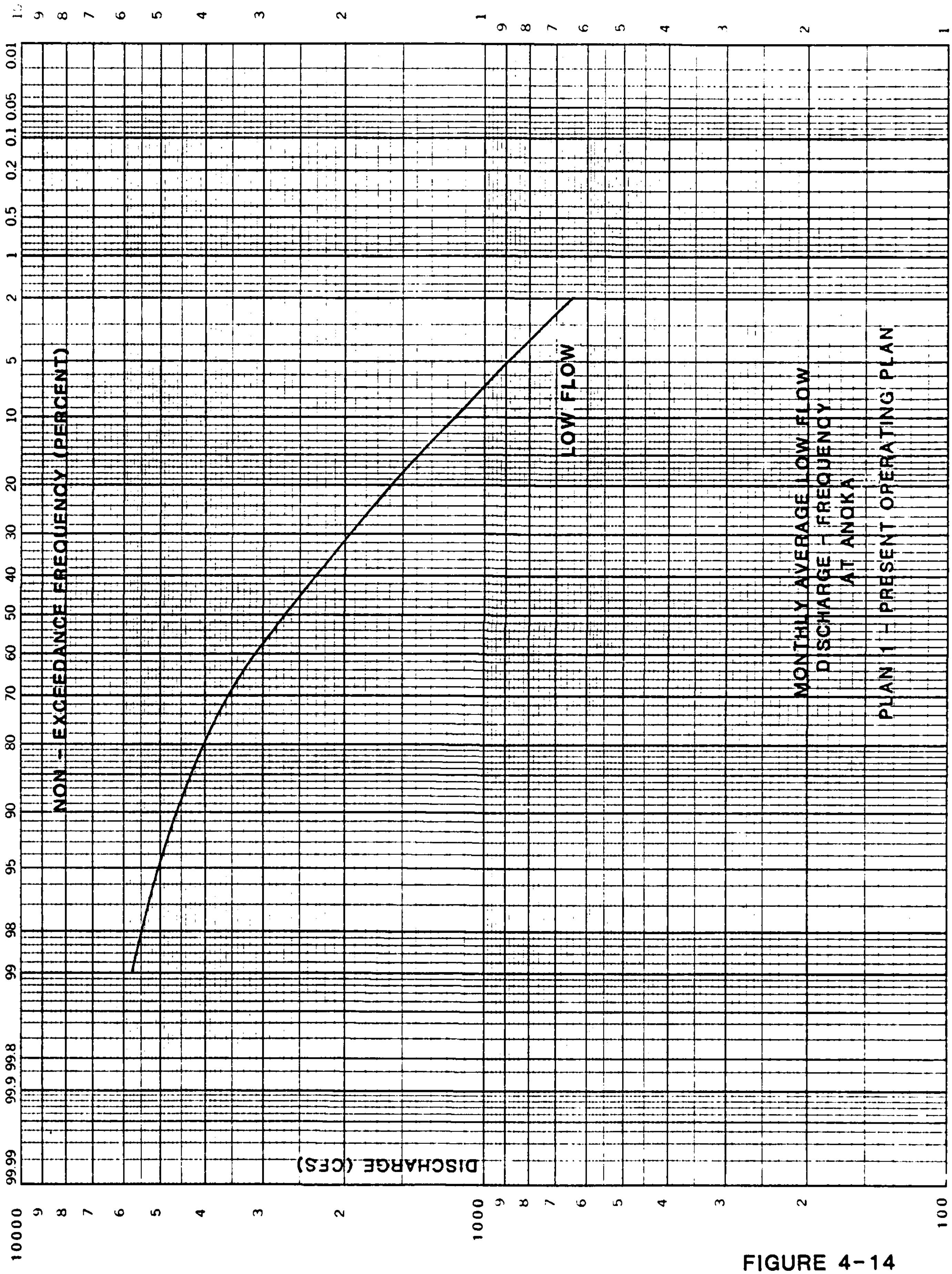

DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
HIGH FLOW
EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)

FIGURE 4-13



NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
LOW FLOW
MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN

FIGURE 4-14

SECTION 5

PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA

OBJECTIVE

This Plan is similar to Plan 1 with the additional objective of maintaining flow at Anoka equal to or greater than 1,600 cfs.

DISCUSSION

This Plan is similar to the Present Operation Plan, Plan 1, in all respects except a minimum flow requirement of 1,600 cfs at Anoka. For purposes of simulation, this is accomplished by operating Pokegama for the 1,600 cfs requirement at Anoka. All other operating rules are the same as Plan 1 including the reservoir index levels shown on Figures 4-1 through 4-6. Sandy, Pine, and Gull are allowed to operate according to Plan 1 criteria because they have relatively small storage compared to the combination of Winnibigoshish, Leech, and Pokegama. As a result, they will not make a significant contribution during low flow periods and their operation for this requirement would unduly increase damages at the reservoir sites.

RESULTS

Although this is a reevaluation of Plan 2 work performed by SAFHL, the simulation results are completely different. As expressed in the SAFHL report (see Reference 1, pg. 139) several monthly periods of water shortage at Anoka (flow below 1,600 cfs) occurred from 1932 through 1938; however, the reservoir storages were not depleted which appeared to be incorrect.

An extensive revision of the HEC-5 conservation tandem reservoir operation logic was performed during this study by HEC. HEC-5 program code changes were made to allow the reservoirs to properly respond to the 1,600 cfs minimum flow requirement at Anoka. During the testing phase of the study, no water shortages occurred at Anoka during the 1930-1976 simulation period. However, when the monthly production runs were later made, it was found that a similar problem had been introduced and water shortages were once again observed at Anoka for three of the 564 monthly periods. HEC was informed of the problem. Prior to HEC's correction of

the problem the St. Paul District decided to use the present set of results for Plan 2 because of time and money constraints. These results include the effect of the HEC-5 problem. Its influence on the hydraulic, frequency, and economic results is discussed below.

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin, and annual minimum flow at Anoka is provided in tables in Appendix F along with a plot of reservoir elevation versus time for each reservoir and streamflow at Aitkin and Anoka. Results shown in the annual minimum flow table include water shortages at Anoka due to the HEC-5 problem. The minimum elevations at Winnibigoshish, Leech, and Pokegama Reservoirs are also affected. Minimum elevations at Winnibigoshish and Leech Reservoirs should be lower in 1934 and 1936, as more water should be released to supply Pokegama Reservoir with extra water to meet the 1,600 cfs flow requirement at Anoka. This additional water may change the minimum elevations at Pokegama Reservoir, depending on the required release from Pokegama to supply Anoka with 1,600 cfs.

Frequency Results

Frequency relationships based upon the 47 years of simulated record are provided on Figures 5-1 through 5-8 for high stage at reservoirs, low stage at reservoirs, high flow at Aitkin, and low flow at Anoka. The HEC-5 problem of not supplying Anoka with a minimum of 1,600 cfs is included in the frequency curves for Winnibigoshish and Leech. Both reservoir frequency curves should be lower for less frequent events (10 to 2 percent exceedance frequency). Anoka's low nonexceedance frequency should not drop below 1,600 cfs, as is shown in Figure 5-8.

Economic Results

Table 5-1 summarizes average annual damage computations and compares this information to Plan 1, Present Operating Plan. Plan 2 is actually able to fully meet the 1,600 cfs minimum flow requirement at Anoka so the low flow average annual cost should be zero, not 630.4 thousand dollars as shown in Table 5-1. The average annual damage (AAD) at Winnibigoshish and Leech is also in error. The low stage damage should be greater for both reservoirs.

The slight decrease in AAD for Leech when compared to the Plan 1 results is unexpected. Rather, one would expect the ADD to increase, as it does for Winnibigoshish and Pokegama Reservoirs when compared to Plan 1 AAD values. The Plan 2 frequency results for Leech Reservoir (Figure 5-2) show only minimal change from Plan 1 unlike Winnibigoshish (Figure 5-1) and Pokegama (Figure 5-3) where the Plan 2 low stage curves are at approximately six and four feet lower elevations, respectively. A detailed analysis of the HEC-5 monthly simulation explains the difference. The Plan 1 results show that Winnibigoshish is constrained from releasing additional flow to balance with Leech's lower levels because Pokegama is at Level 4 for most of the time. In Plan 2 Pokegama releases more water to try to supply a minimum of 1,600 cfs to Anoka. This lowers Pokegama's level and, in turn, allows Winnibigoshish to release additional flow to Pokegama. Winnibigoshish's levels drop to between Level 1 and Level 2 and are approximately equal to Leech's levels. Leech's low stage levels and elevations change minimally between Plan 1 and Plan 2 and only in the range of 50 to 10 percent exceedance frequency. This change (higher Leech low stages in Plan 2 compared to Plan 1) results from a difference in the March 1930 Leech outflow for the two plans. The conditions for the preceeding months at Winnibigoshish and Leech are identical for the two plans; the conditions at Pokegama differ only slightly. For Plan 1 Leech releases 745 cfs in March 1930; for Plan 2 the release is 100 cfs. This results in a difference in elevation for the two plans of approximately 0.2 feet, with the Plan 1 elevation lower. This difference affects the low stage results for four years (1930-1933) before the two plans coverage again. And this difference produces the slightly higher low stage frequency curve and correspondingly smaller low stage AAD at Leech for Plan 2. This also demonstrates the complexity and sensitivity of the decision process in HEC-5 in determining size of reservoir releases.

The total AAD for Plan 2 is only slightly higher than for Plan 1, and would not be substantially higher even if the HEC-5 problem was not affecting the results. The Plan 2 economic benefits of supplying Anoka with 1,600 cfs are much greater than the total AAD at the reservoirs and Aitkin. Using the rate of $385 per cfs-day, the benefit gained by Plan 2 over Plan 1 is worth $2,559.5 thousand.

TABLE 5-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 2	PLAN 1
Winnibigoshish		
High Stage	4.0	4.0
Low Stage	16.6	9.7
Total	20.6	13.7
Leech		
High Stage	10.6	11.0
Low Stage	66.5	71.3
Total	77.1	82.3
Pokegama		
High Stage	24.9	25.0
Low Stage	8.1	2.8
Total	33.0	27.8
Sandy		
High Stage	29.4	29.4
Low Stage	2.1	2.1
Total	31.5	31.5
Pine		
High Stage	16.6	16.6
Low Stage	6.3	6.3
Total	22.9	22.9
Gull		
High Stage	127.5	127.5
Low Stage	15.2	15.2
Total	142.7	142.7
Aitkin		
High Flow	278.6	278.6
TOTAL AAD	606.4	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	630.4*	3,189.9

*should actually be 0.0

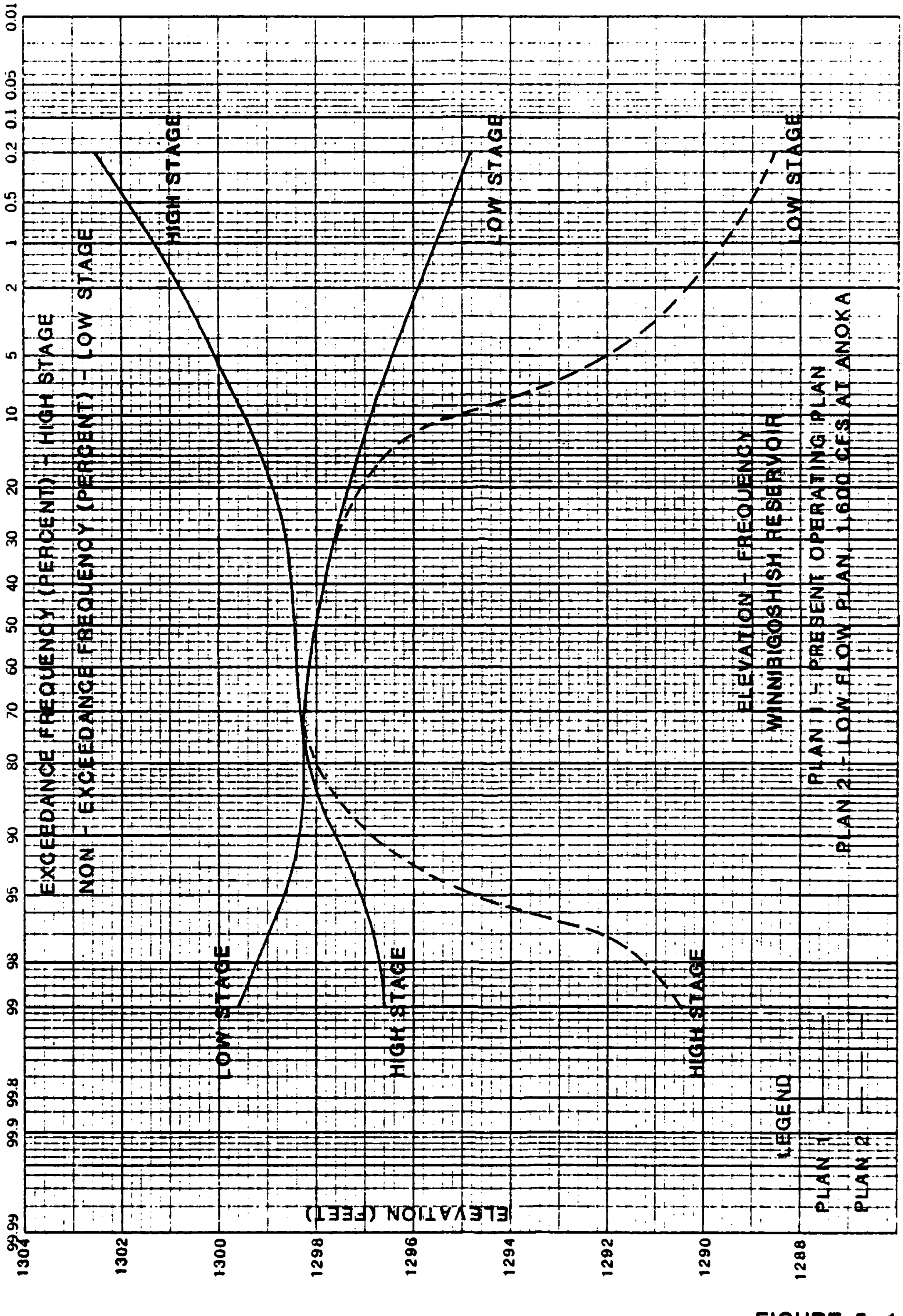

ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 2
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1304
1302
1300
1298
1296
1294
1292
1290
1288

FIGURE 5-1

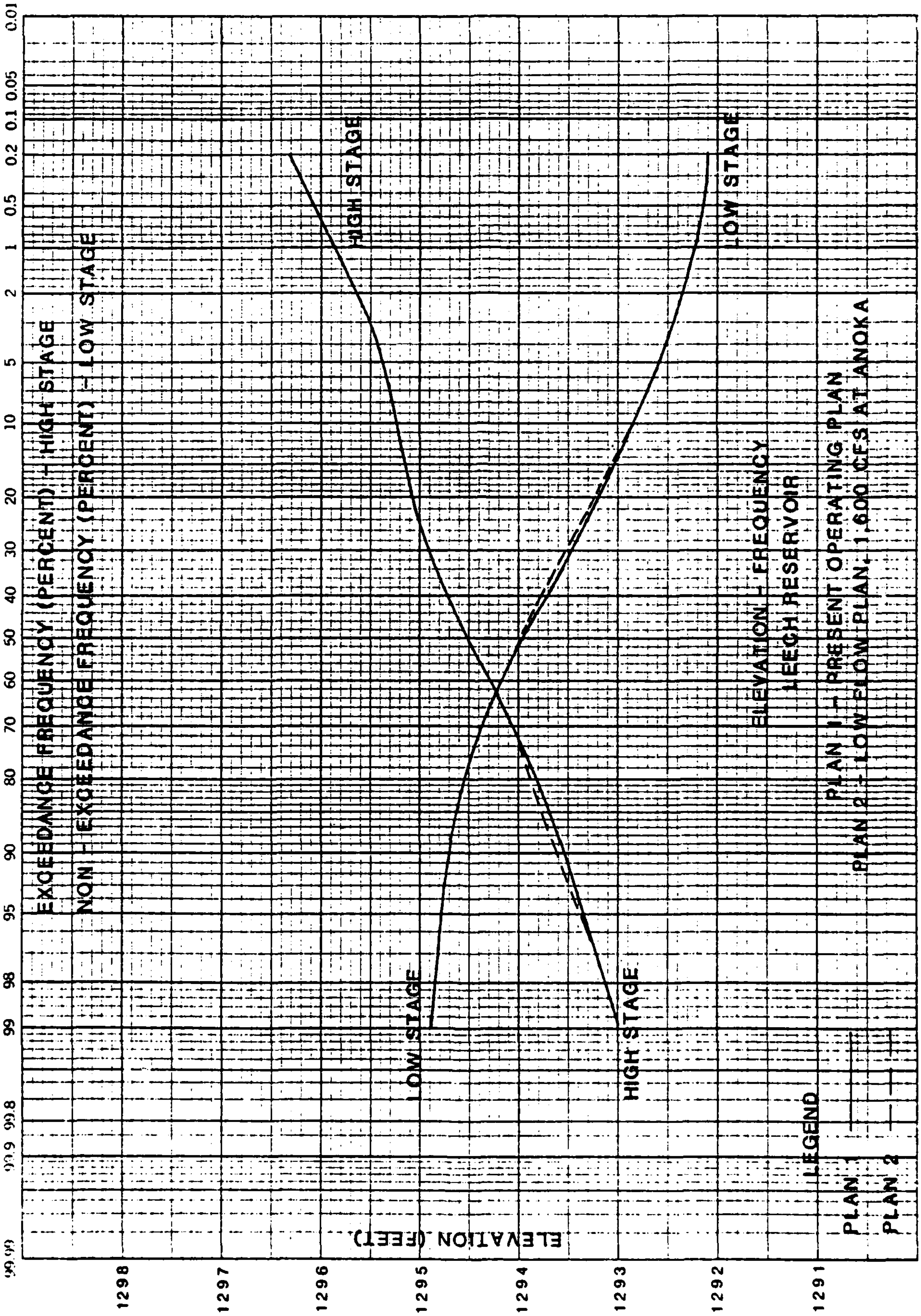
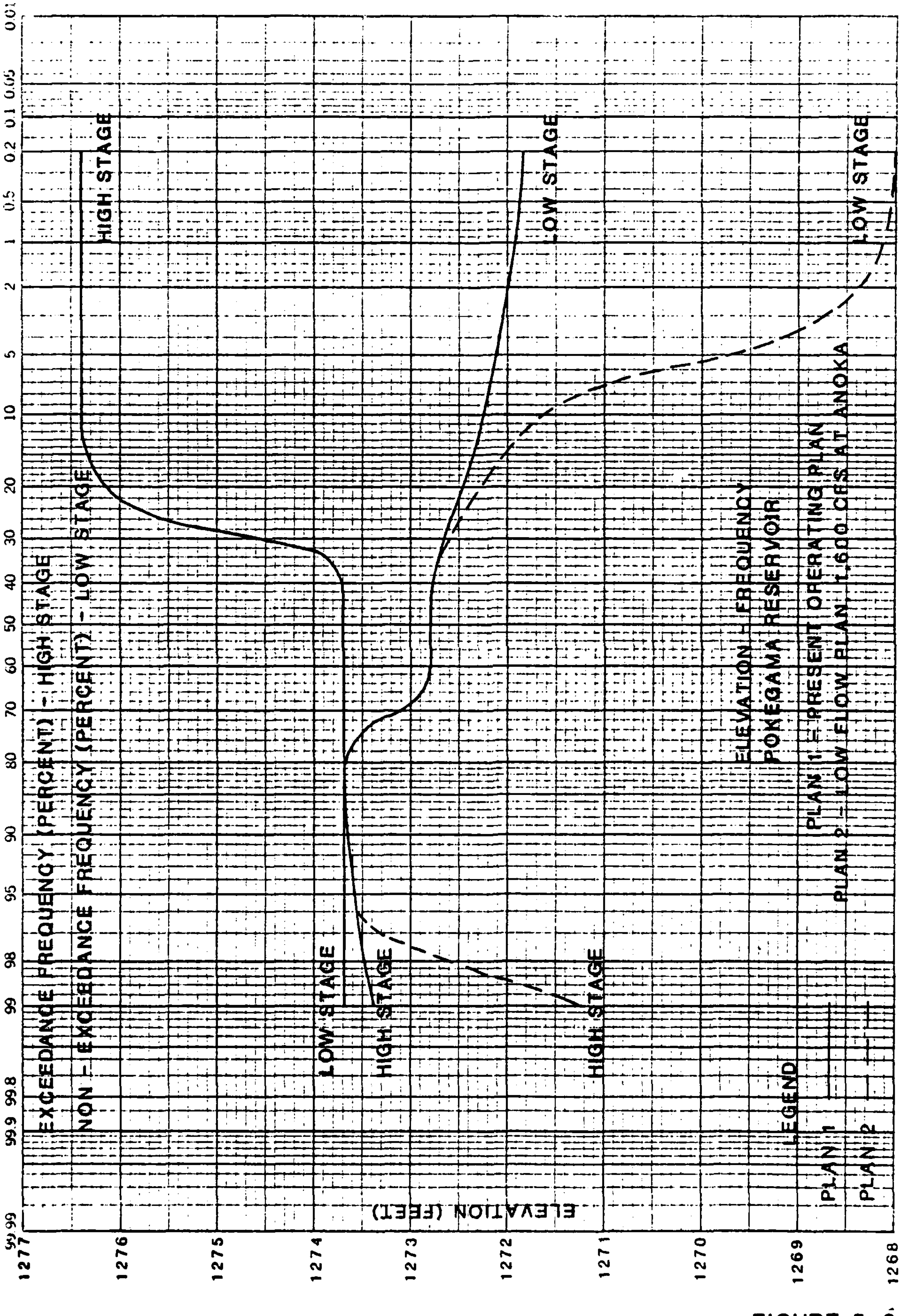

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA
LEGEND
PLAN 1
PLAN 2
ELEVATION (FEET)
1298
1297
1296
1295
1294
1293
1292
1291

FIGURE 5-2



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 = PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN 1,600 CFS AT ANOKA
LEGEND
PLAN 1
PLAN 2
ELEVATION (FEET)
1277
1276
1275
1274
1273
1272
1271
1270
1269
1268

FIGURE 5-3

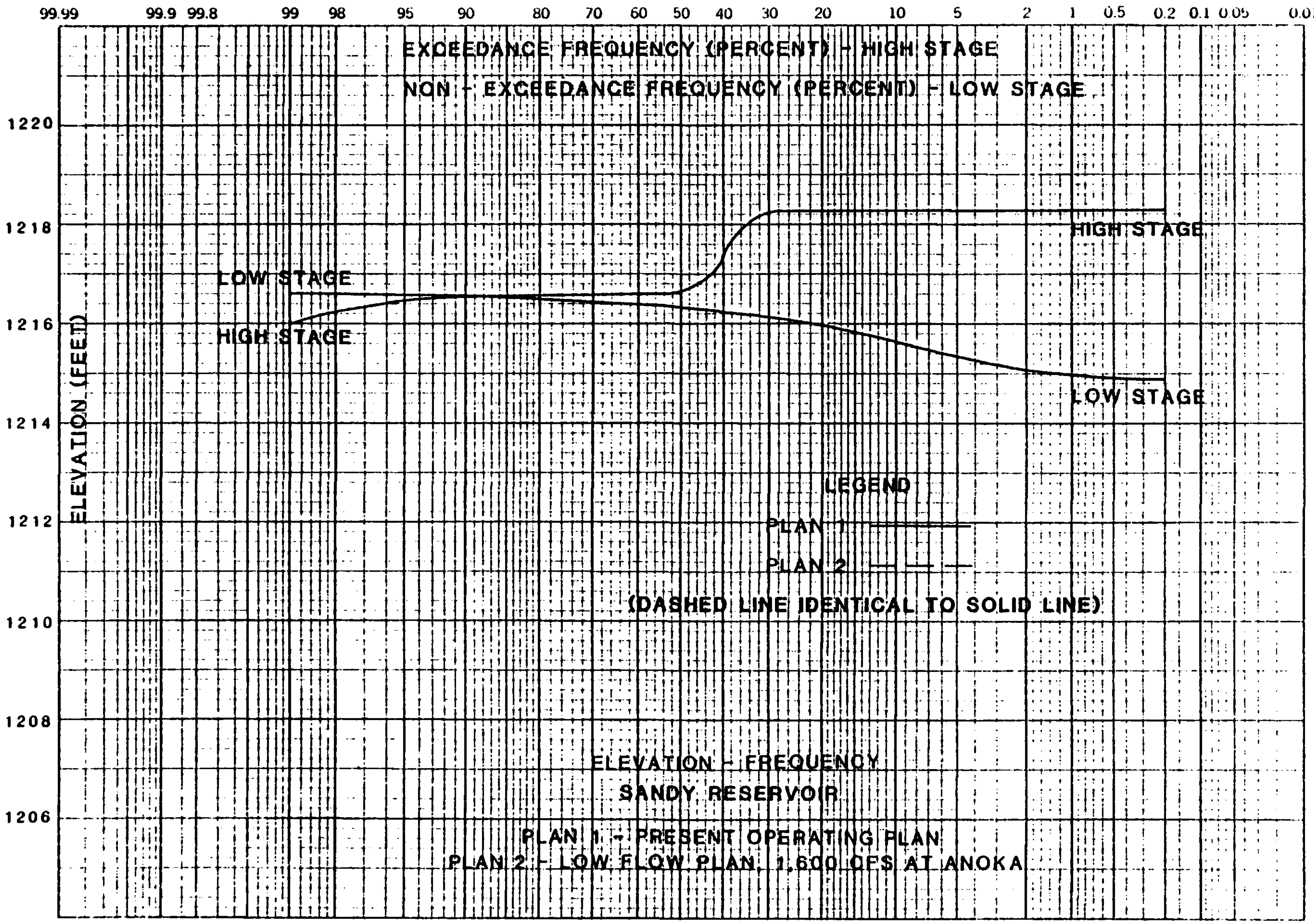

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1220
1218
1216
1214
1212
1210
1208
1206
ELEVATION (FEET)
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 2
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA

FIGURE 5-4

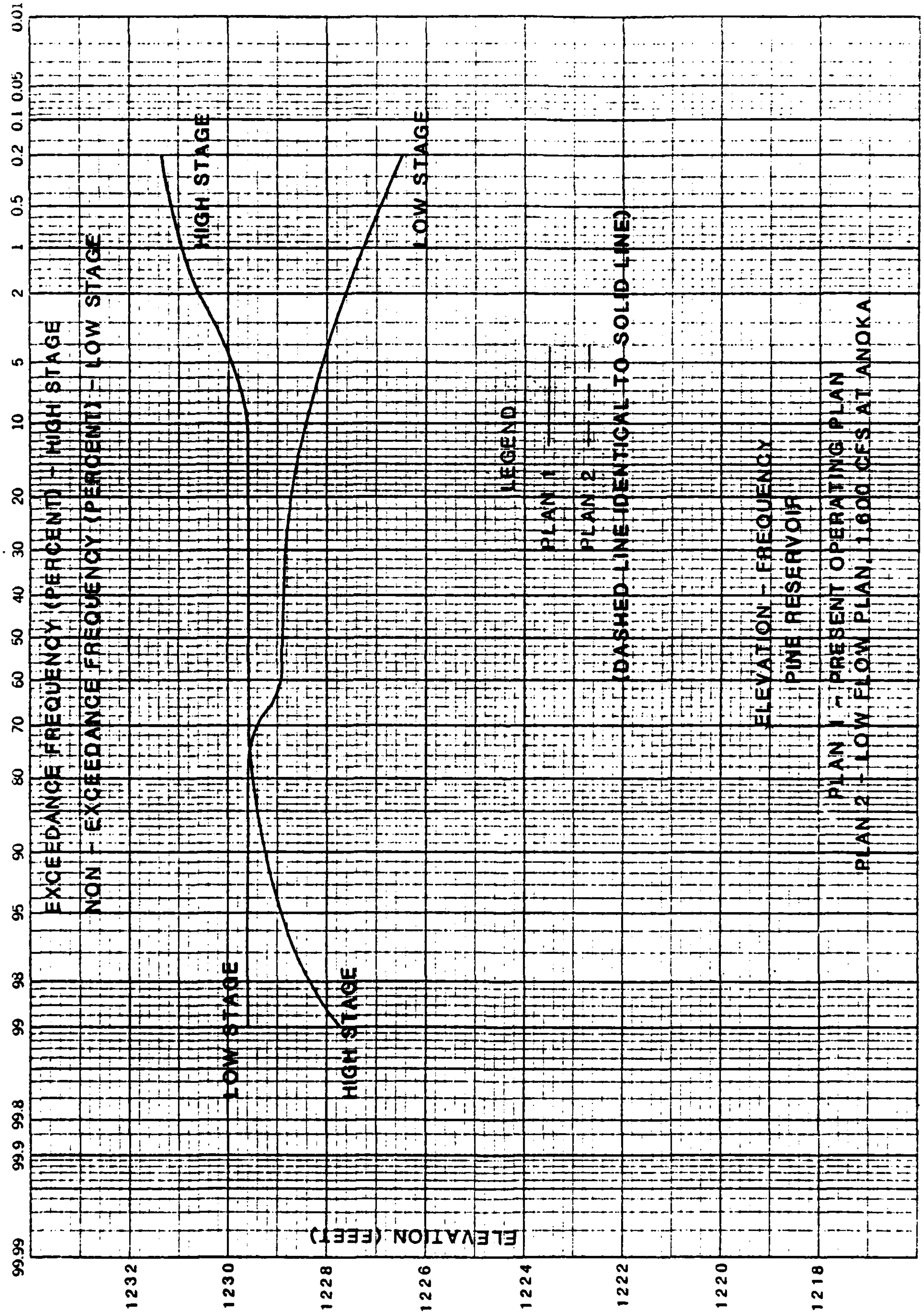
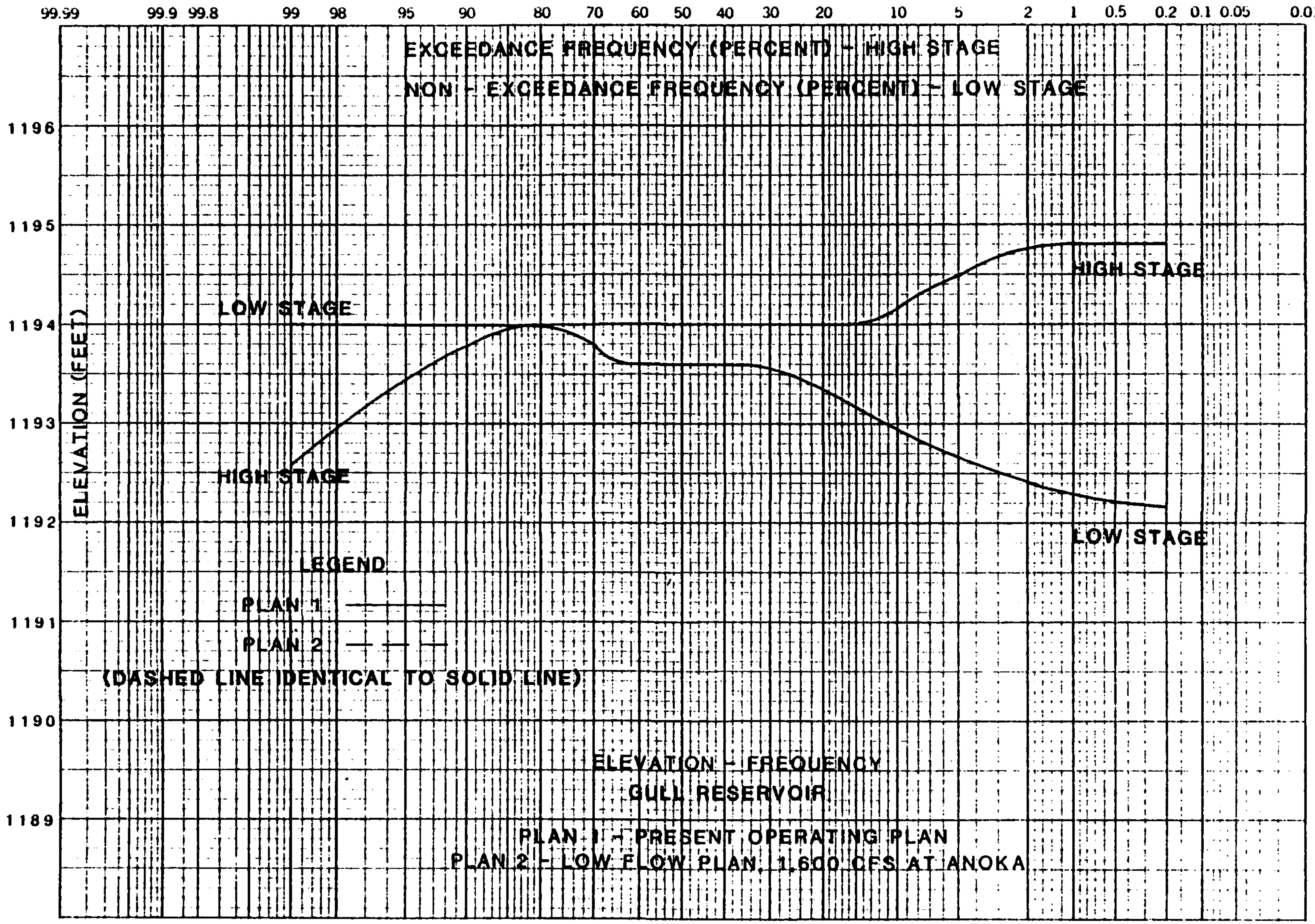
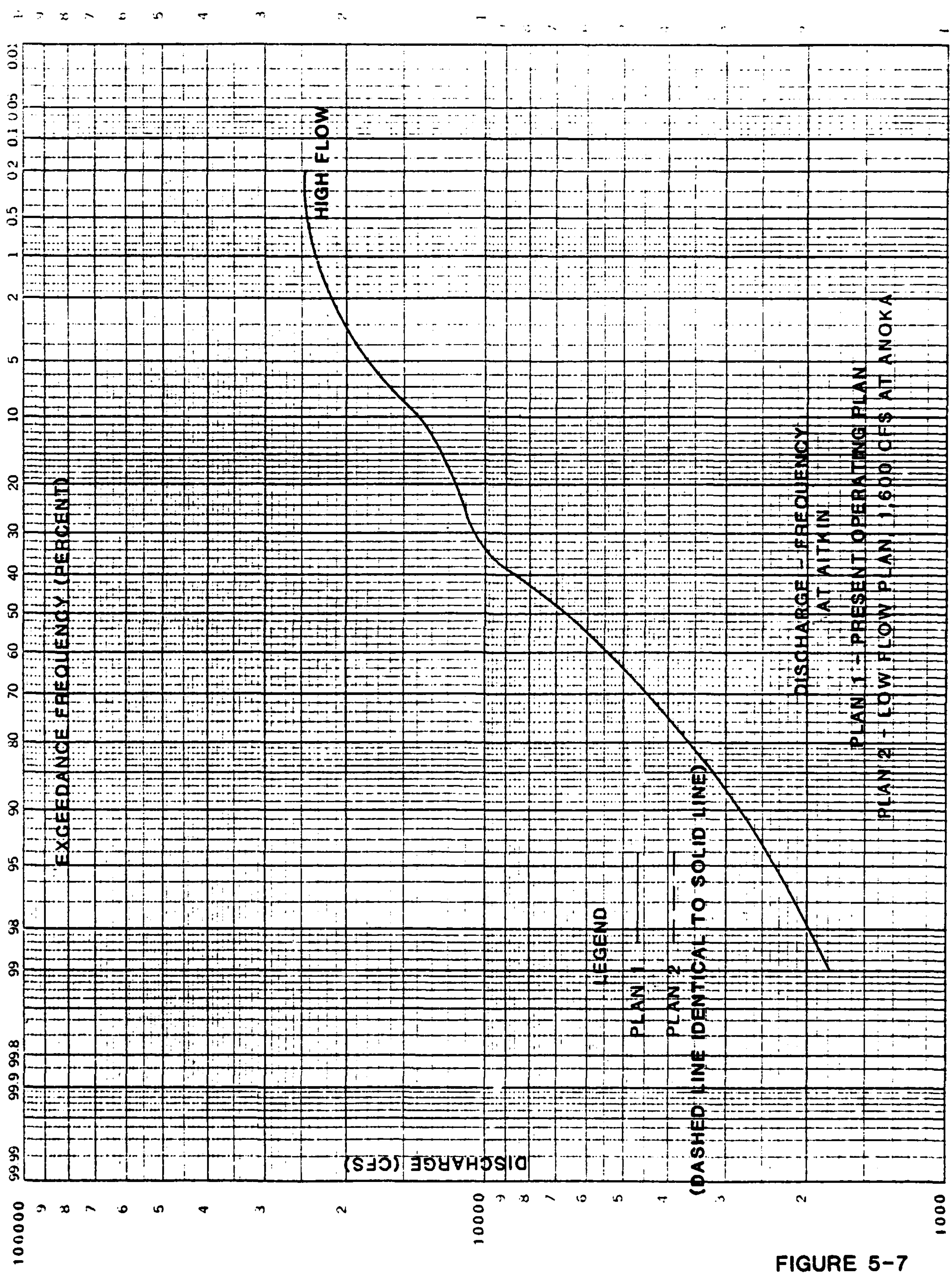

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 2
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA
ELEVATION (FEET)
1232
1230
1228
1226
1224
1222
1220
1218
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

FIGURE 5-5



99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
1196
1195
1194
1193
1192
1191
1190
1189
ELEVATION (FEET)
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 2
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA

FIGURE 5-6



DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN 1,600 CFS AT ANOKA
EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
LEGEND
PLAN 1
PLAN 2
(DASHED LINE IDENTICAL TO SOLID LINE)

FIGURE 5-7

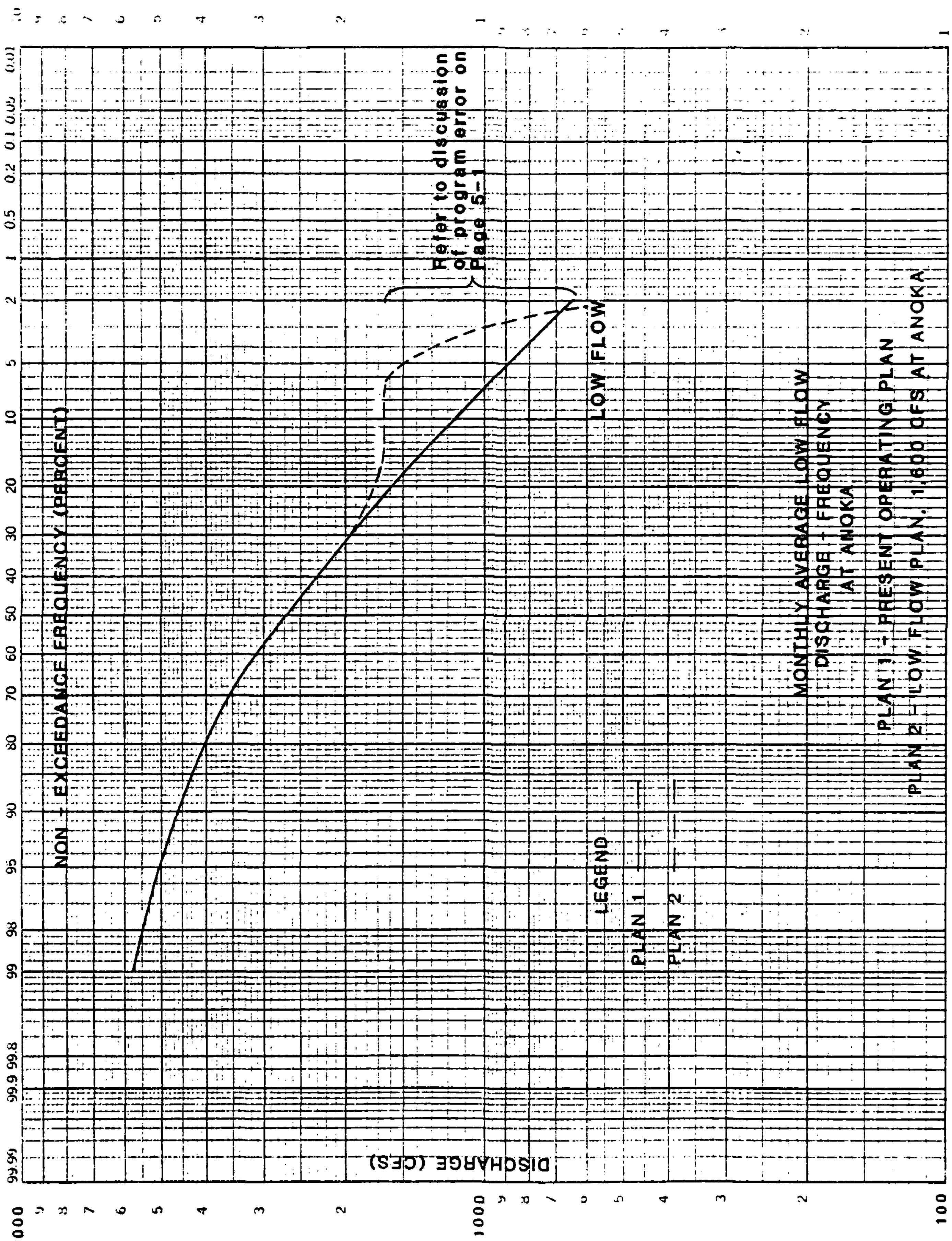

MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 2 - LOW FLOW PLAN, 1,600 CFS AT ANOKA
NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
LOW FLOW
Refer to discussion
of program error on
Page 5-1
LEGEND
PLAN 1
PLAN 2
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
10000
1000
100

FIGURE 5-8

SECTION 6

PLAN 3 - HIGH FLOW PLAN

OBJECTIVE

The primary objective of the high flow plan is to provide increased flood protection at Aitkin.

DISCUSSION

This is a reevaluation of the work performed by SAFHL and conforms to the description provided in their final report (Reference 1, pp. 46-50). The operating criteria for the four reservoirs above Aitkin are changed to provide more space for storing spring snowmelt. This is accomplished by providing a lower drawdown in the early spring as shown on the reservoir index level rules, Figures 6-1 through 6-4. Index levels for Pine and Gull remain unchanged from Plan 1, see Figures 4-5 and 4-6. The SAFHL procedure changed the summer target level stage at Winnibigoshish from the Plan 1 values of 9.0 - 9.5 feet to 10.0 - 10.5 feet for Plan 3. This was not done in this study; the summer target level at Winnibigoshish is the same for Plans 1 and 3, 9.0 - 9.5 feet.

RESULTS

As explained in Section 4 for Plan 1, the results in the early 1930's are different than the SAFHL results due to different reservoir storage values in January 1932. However, the results quickly converge and closely approximate the SAFHL values.

A comparison of the maximum flows at Aitkin between Plan 3 and Plan 1 shows the number of floods above 11,200 cfs decreases from 10 (Plan 1) to six (Plan 3). The largest flow (May 1950) is the same for both plans (approximately 21,600 cfs). The recorded flow for this flood is approximately 18,000 cfs at Aitkin. Note that the HEC-5 results always include the flow in the diversion channel at Aitkin.

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin and annual minimum flow at Anoka is provided in tables in Appendix G. A plot of reservoir elevation versus time is also included in Appendix G for each reservoir together with the streamflow at Aitkin and Anoka.

Plan 3 decreases the number and size of the flood flows at Aitkin compared to Plan 1. This operation plan is successful in each year of major flooding except 1950, when local inflows uncontrolled by reservoirs exceed 14,000 cfs and Pokegama Reservoir is above flood pool stage (Level 5) and must release all inflows. This also occurs in Plan 1.

Frequency Results

Frequency relationships based upon the 47 years of simulated record are provided in Figures 6-5 through 6-12 for high stage at reservoirs, low stage at reservoirs, high flow at Aitkin, and low flow at Anoka.

Economic Results

Table 6-1 summarizes average annual damage computations and compares this information to Plan 1, Present Operating Plan. The objective of Plan 3 is to minimize high flow damage at Aitkin compared to Plan 1. This objective is accomplished with a 22 percent reduction in average annual high flow damage at Aitkin. However, Plan 3 also creates greater average annual damages (AAD) at Winnibigoshish, Leech, Pokegama, and Sandy Reservoirs. This increase in AAD for these four reservoirs is $265.9K (171 percent) and is much larger than the $61.8K saved at Aitkin over Plan 1. Overall, the AAD for Plan 3 increases by 34 percent over Plan 1. The average annual cost (AAC) of not supplying a minimum of 1600 cfs at Anoka was also calculated for Plan 3, although it was not the explicit purpose of Plan 3 to meet this requirement. However, by calculating the AAC it was then possible to compare the Plan 3 average annual net benefit (or cost) relative to Plan 1. The AAC for Plan 3 is $3707.2K compared to $3189.9K for Plan 1. The relative net cost of Plan 3 at Anoka is $517.3K.

TABLE 6-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 3	PLAN 1
Winnibigoshish		
High Stage	0.1	4.0
Low Stage	73.3	9.7
Total	73.4	13.7
Leech		
High Stage	9.6	11.0
Low Stage	166.8	71.3
Total	176.4	82.3
Pokegama		
High Stage	18.7	25.0
Low Stage	14.0	2.8
Total	32.7	27.8
Sandy		
High Stage	26.8	29.4
Low Stage	111.9	2.1
Total	138.7	31.5
Pine		
High Stage	16.6	16.6
Low Stage	6.3	6.3
Total	22.9	22.9
Gull		
High Stage	127.5	127.5
Low Stage	15.2	15.2
Total	142.7	142.7
Aitkin		
High Flow	216.8	278.6
TOTAL AAD	803.6	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	3707.2	3,189.9

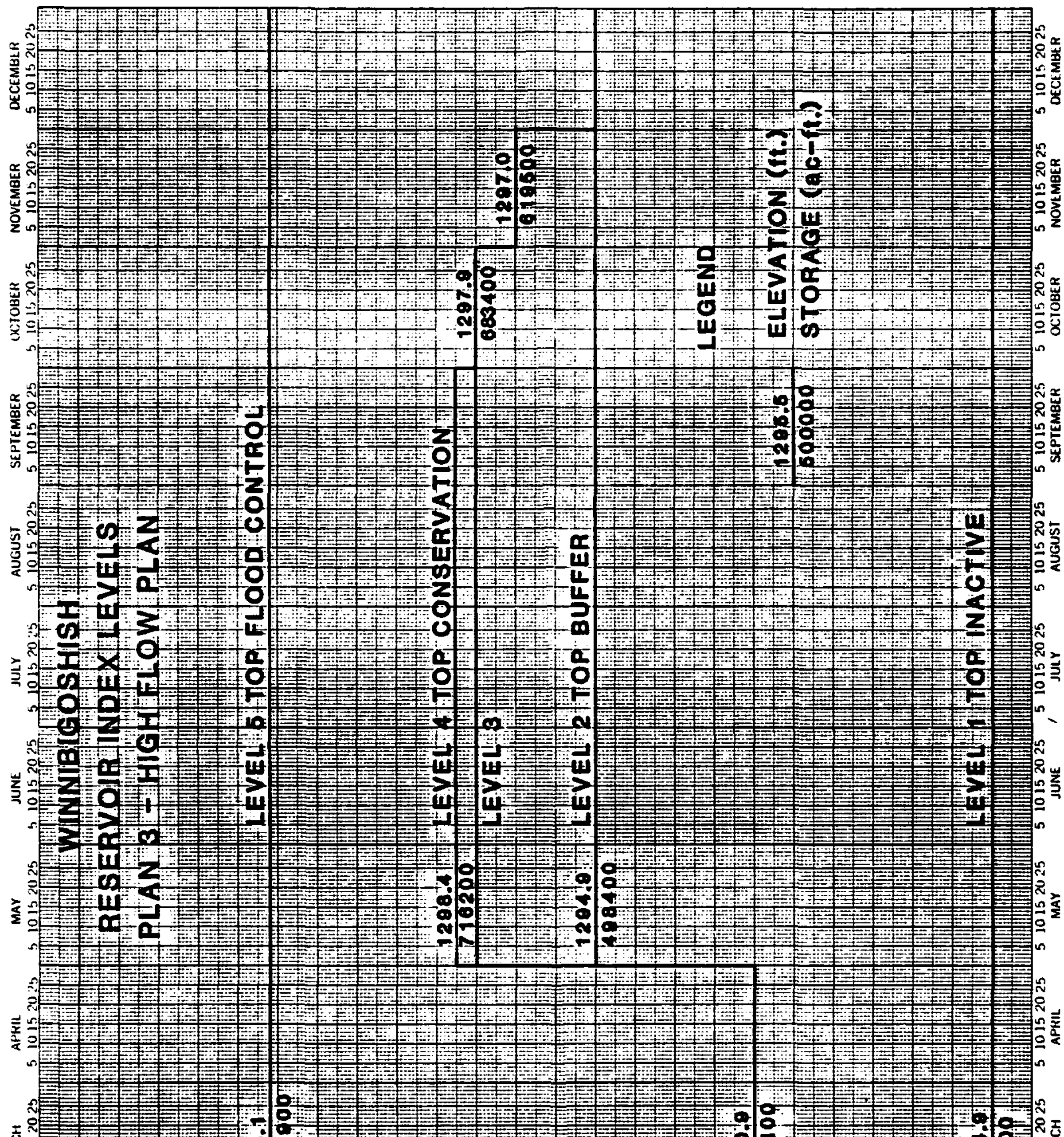

WINNIBIGOSHISH
RESERVOIR INDEX LEVELS
PLAN 3 - HIGH FLOW PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
1303.1
1151900
1292.9
389600
1290.9
283100
1284.9
24000
1298.4
716200
1294.9
498400
1297.9
683400
1297.0
619500
1295.5
500000
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 6-1

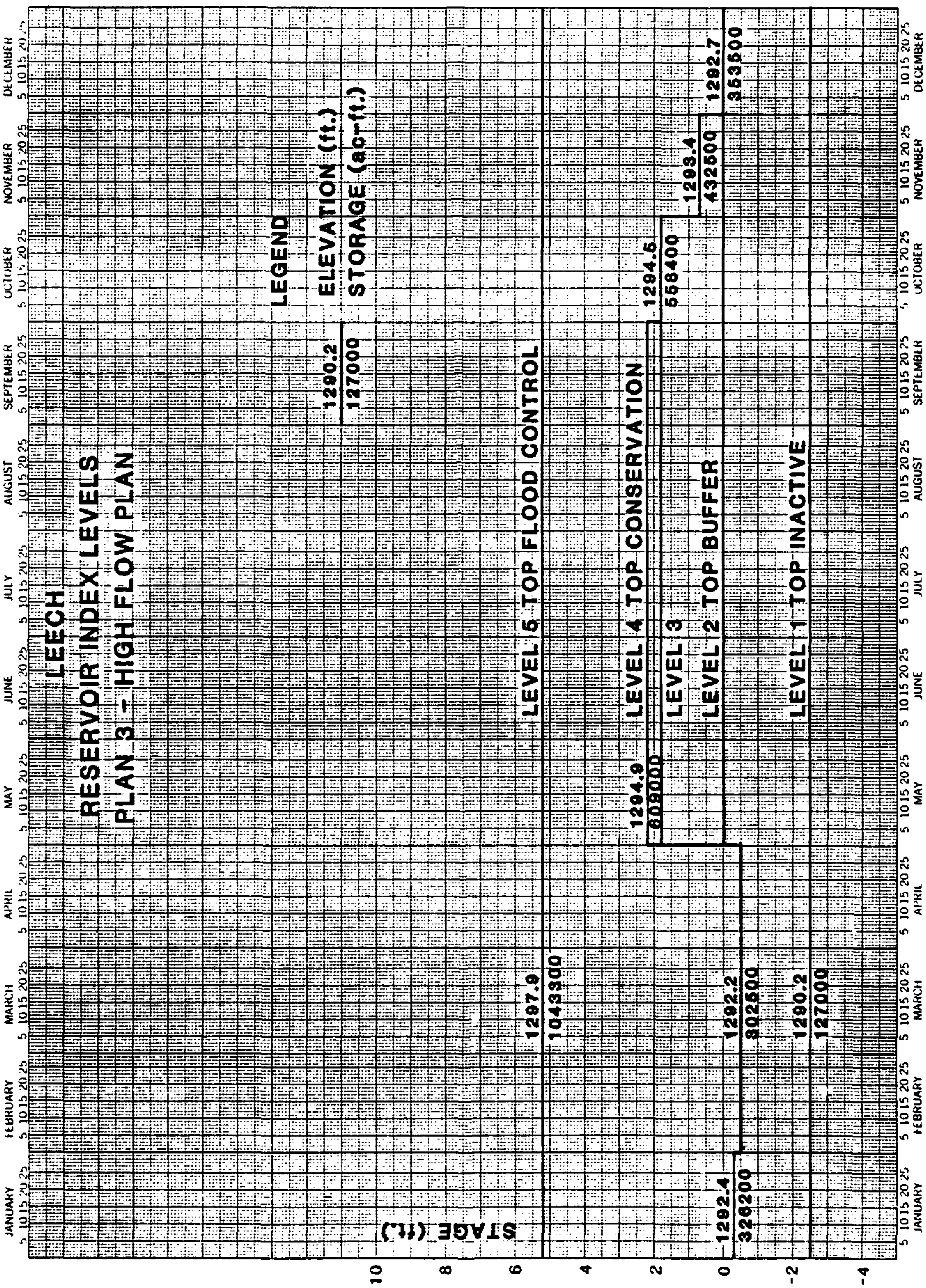

LEECH
RESERVOIR INDEX LEVELS
PLAN 3 - HIGH FLOW PLAN
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
STAGE (ft.)
1297.9
1043300
1294.9
609000
1294.5
558400
1293.4
432500
1292.7
353500
1292.4
326200
1292.2
302500
1290.2
127000
1290.2
127000
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 6-2

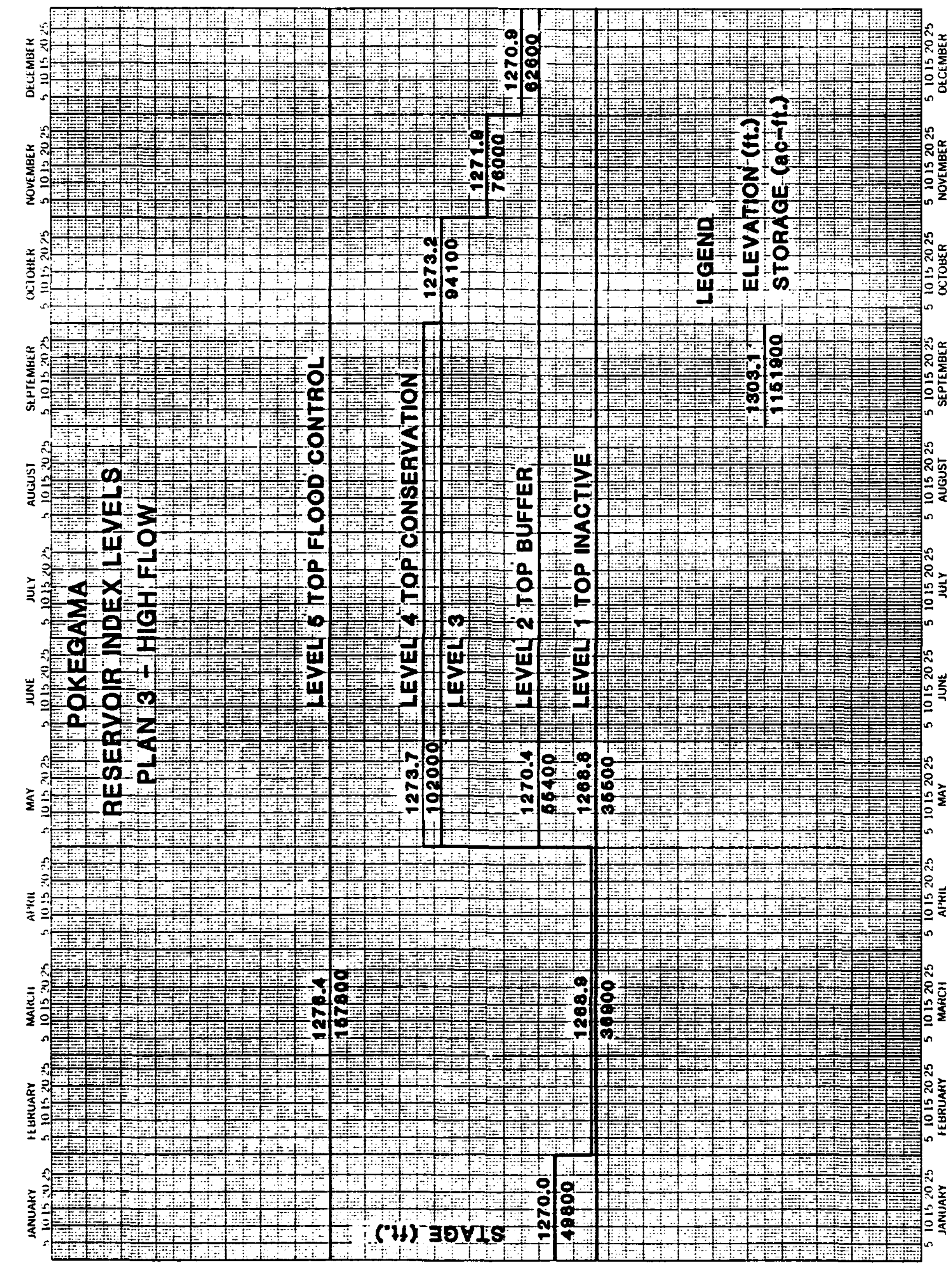

POKEGAMA
RESERVOIR INDEX LEVELS
PLAN 3 - HIGH FLOW
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
1303.1
1151900
STAGE (ft.)
12
10
8
6
4
2
0
-2
-4
1270.0
49800
1276.4
167800
1268.8
36900
1273.7
102000
1270.4
55400
1268.8
36500
1273.2
94100
1271.8
76000
1270.9
62800
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25

FIGURE 6-3

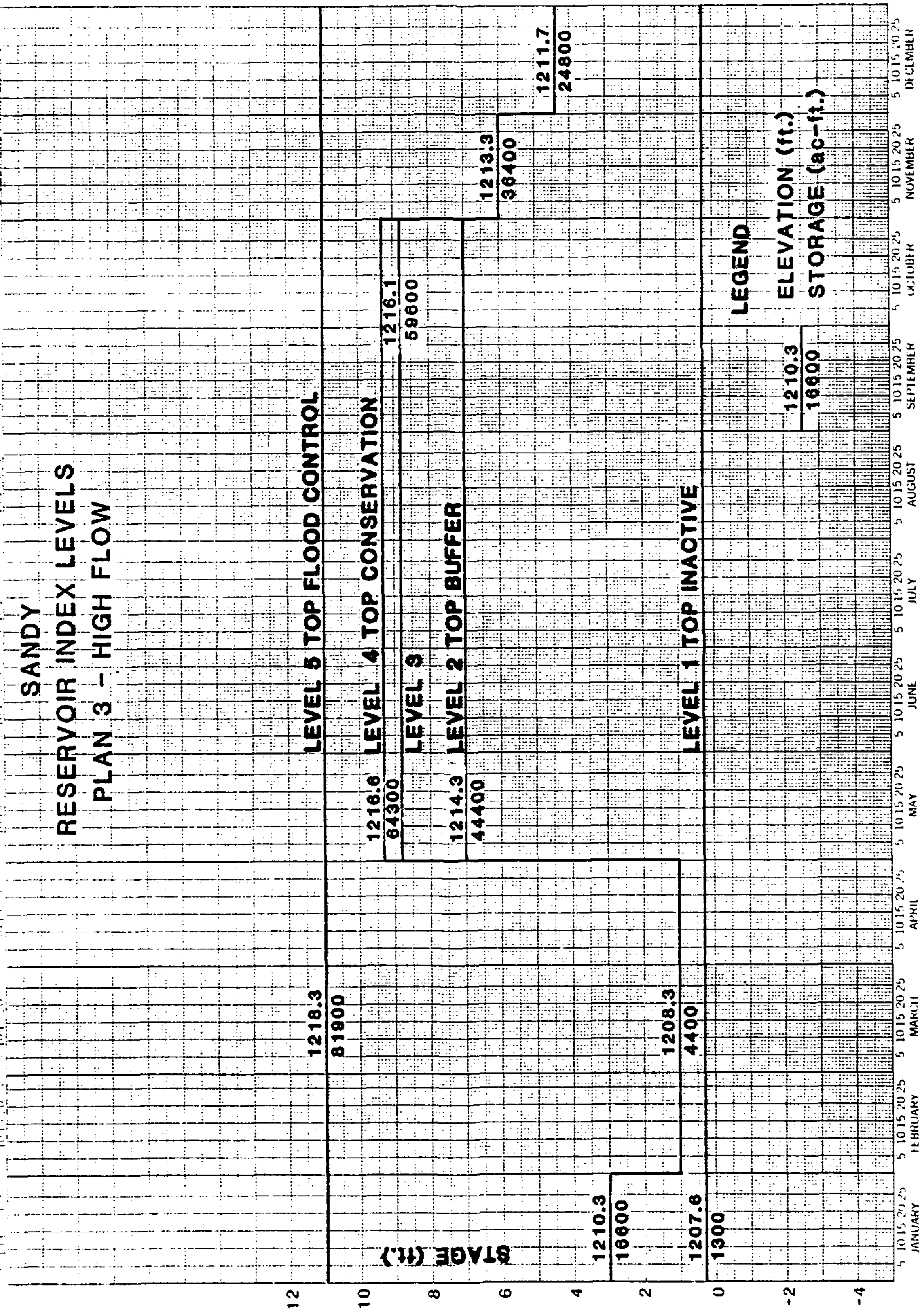

SANDY
RESERVOIR INDEX LEVELS
PLAN 3 - HIGH FLOW
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
1210.3
16600
1218.3
81900
1208.3
4400
1207.6
1300
1216.6
64300
1214.3
44400
1216.1
59600
1213.3
36400
1211.7
24800
STAGE (ft.)
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 6-4

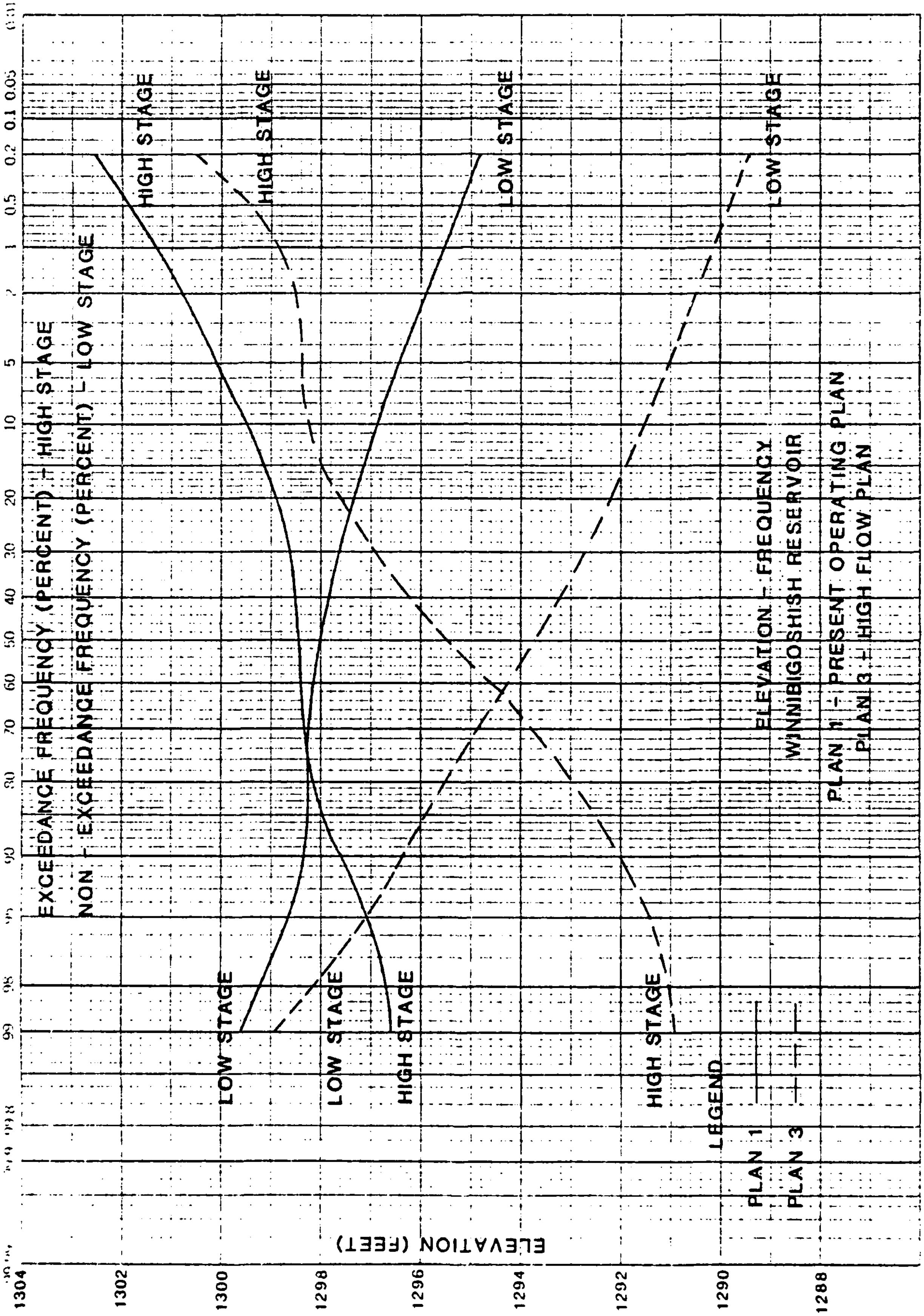
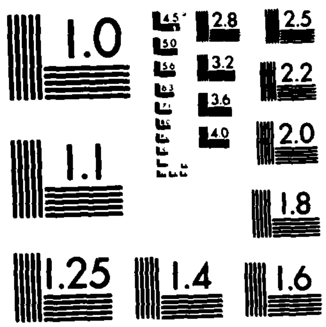

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
HIGH STAGE
LOW STAGE
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
LEGEND
PLAN 1
PLAN 3
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
98
99
1304
1302
1300
1298
1296
1294
1292
1290
1288

FIGURE 6-5

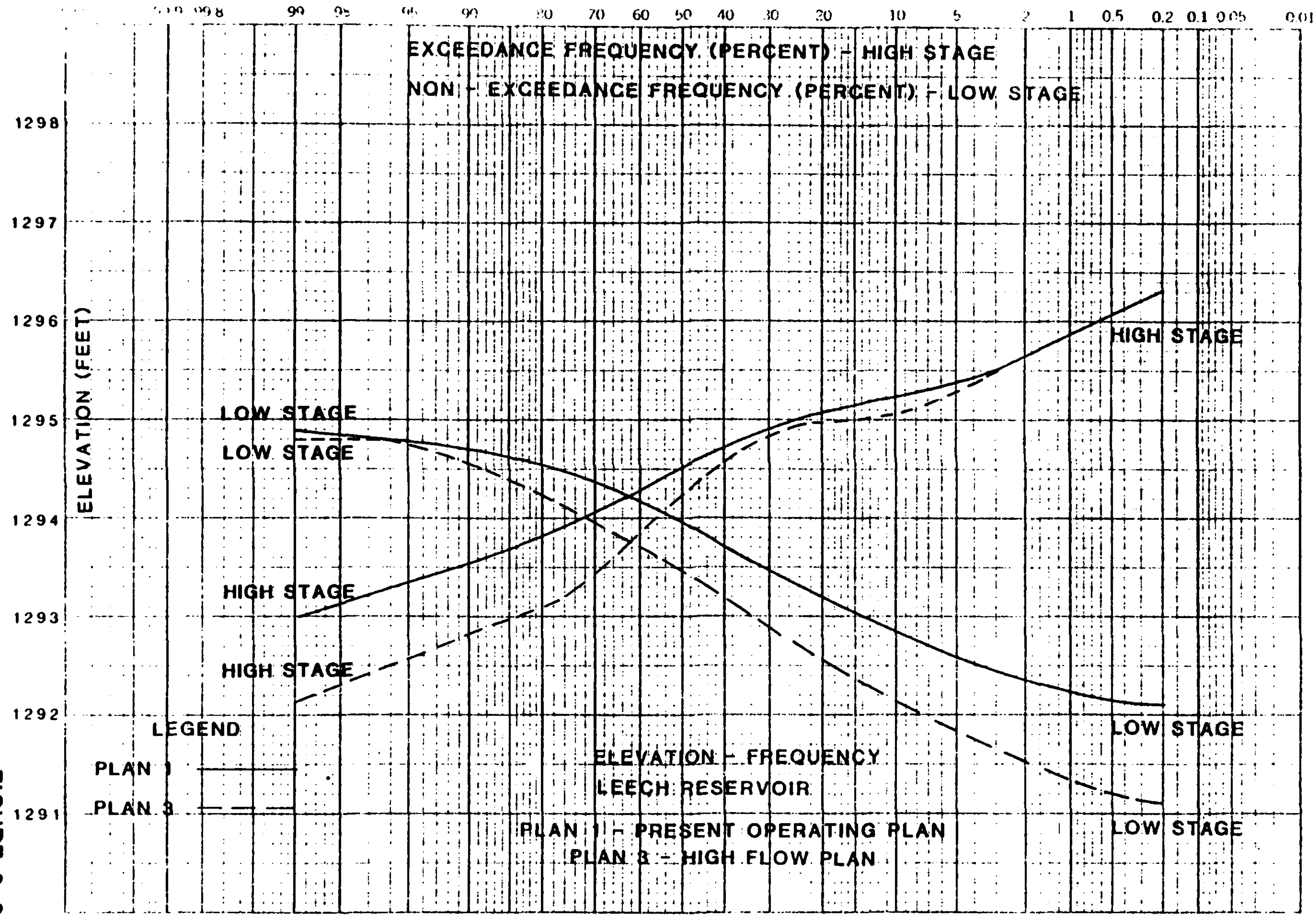
AD-A146 708 COMPUTER OPERATIONS STUDY OF RESERVOIR OPERATIONS FOR SIX MISSISSIPPI RIVER HEADWATERS DAMS(U) ANDERSON-NICHOLS AND CO INC PALO ALTO CA A SLOCUM ET AL. JUN 82 DACW37-81-C-0027 2/2

UNCLASSIFIED F/G 13/2 NL

END



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
ELEVATION (FEET)
1298
1297
1296
1295
1294
1293
1292
1291
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 3
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN

FIGURE 6-6

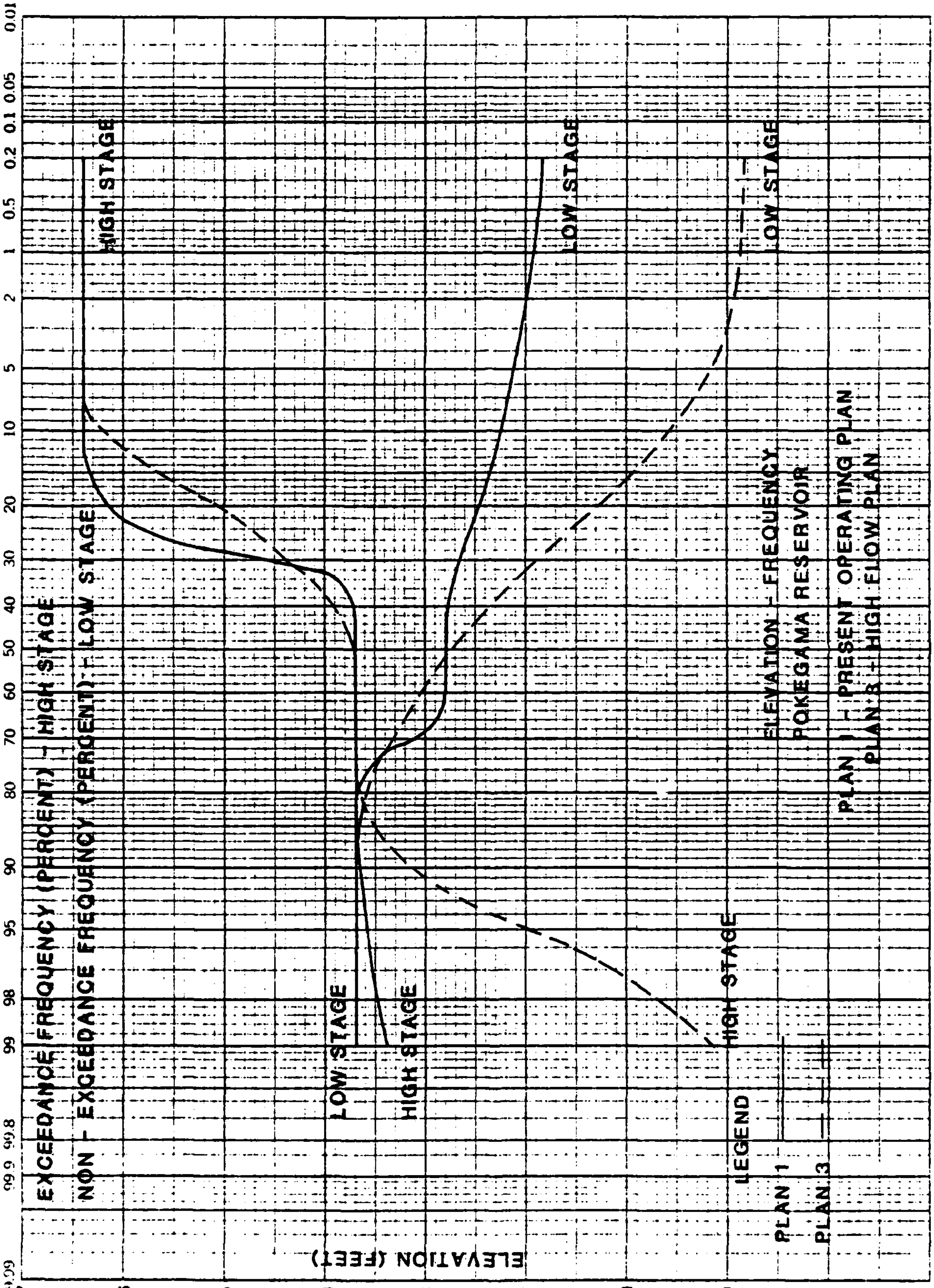

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1277
1276
1275
1274
1273
1272
1271
1270
1269
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
LEGEND
PLAN 1
PLAN 3

FIGURE 6-7

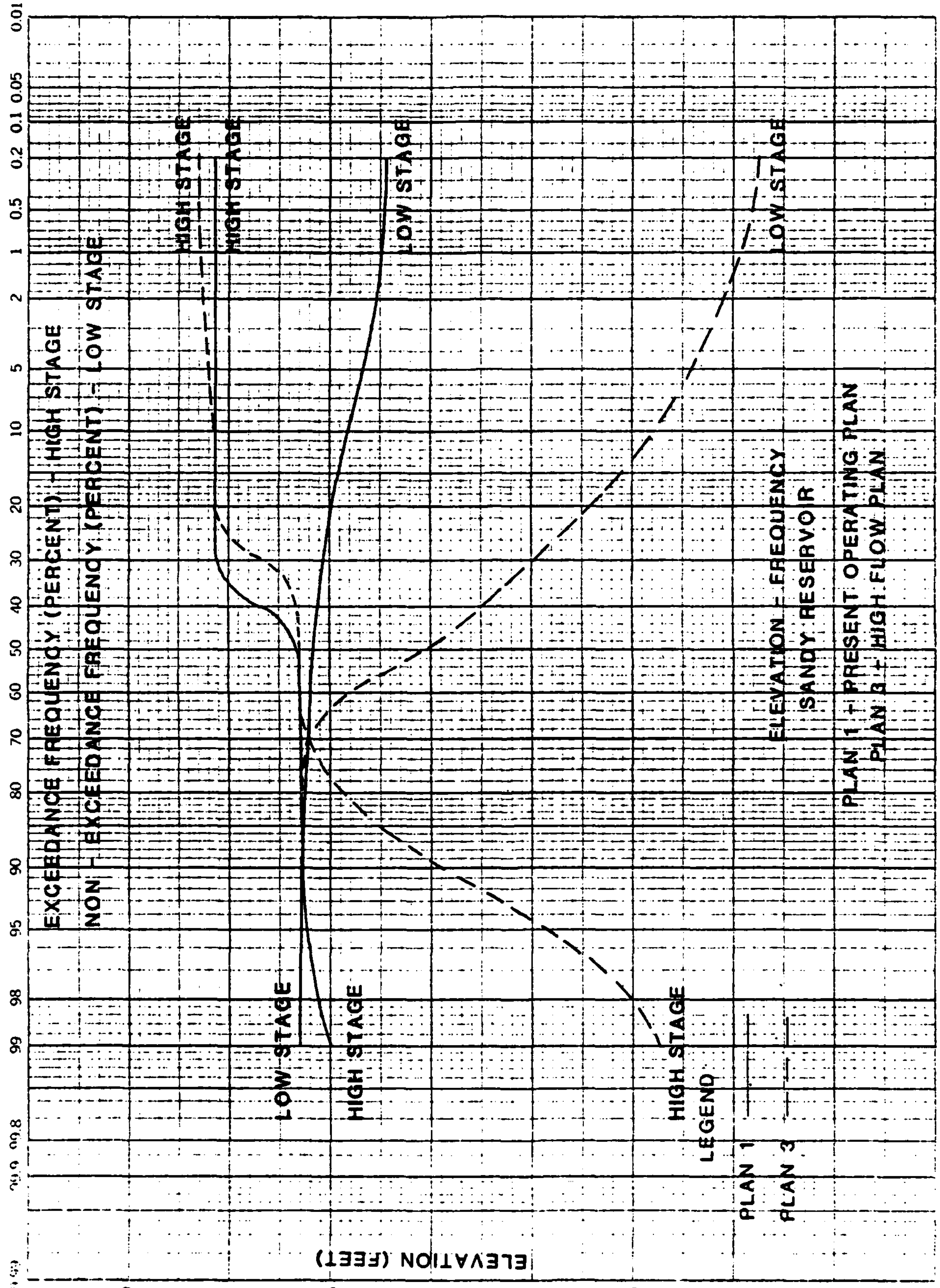

ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
LEGEND
PLAN 1
PLAN 3
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
HIGH STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
1220
1218
1216
1214
1212
1210
1208
1206

FIGURE 6-8

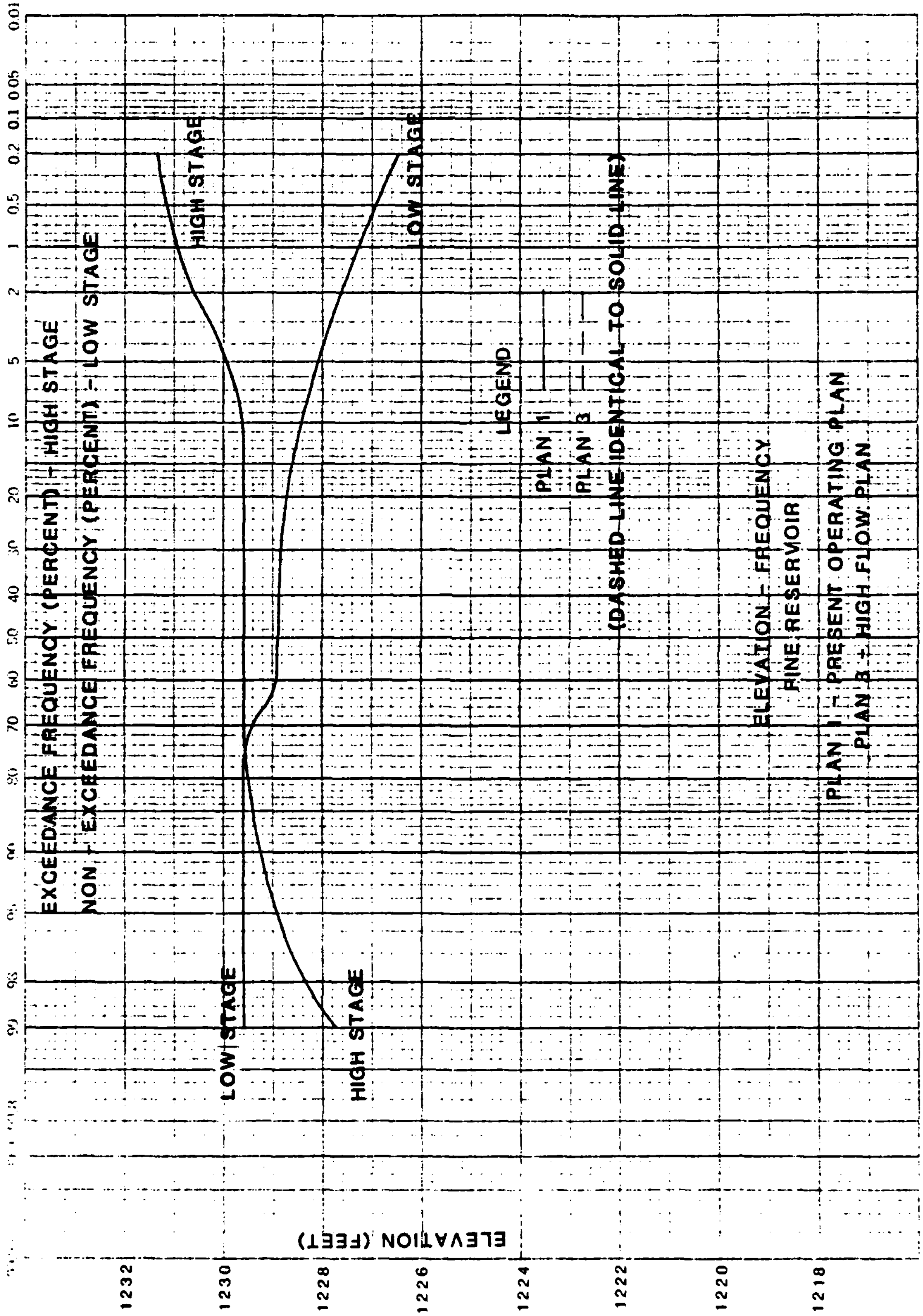
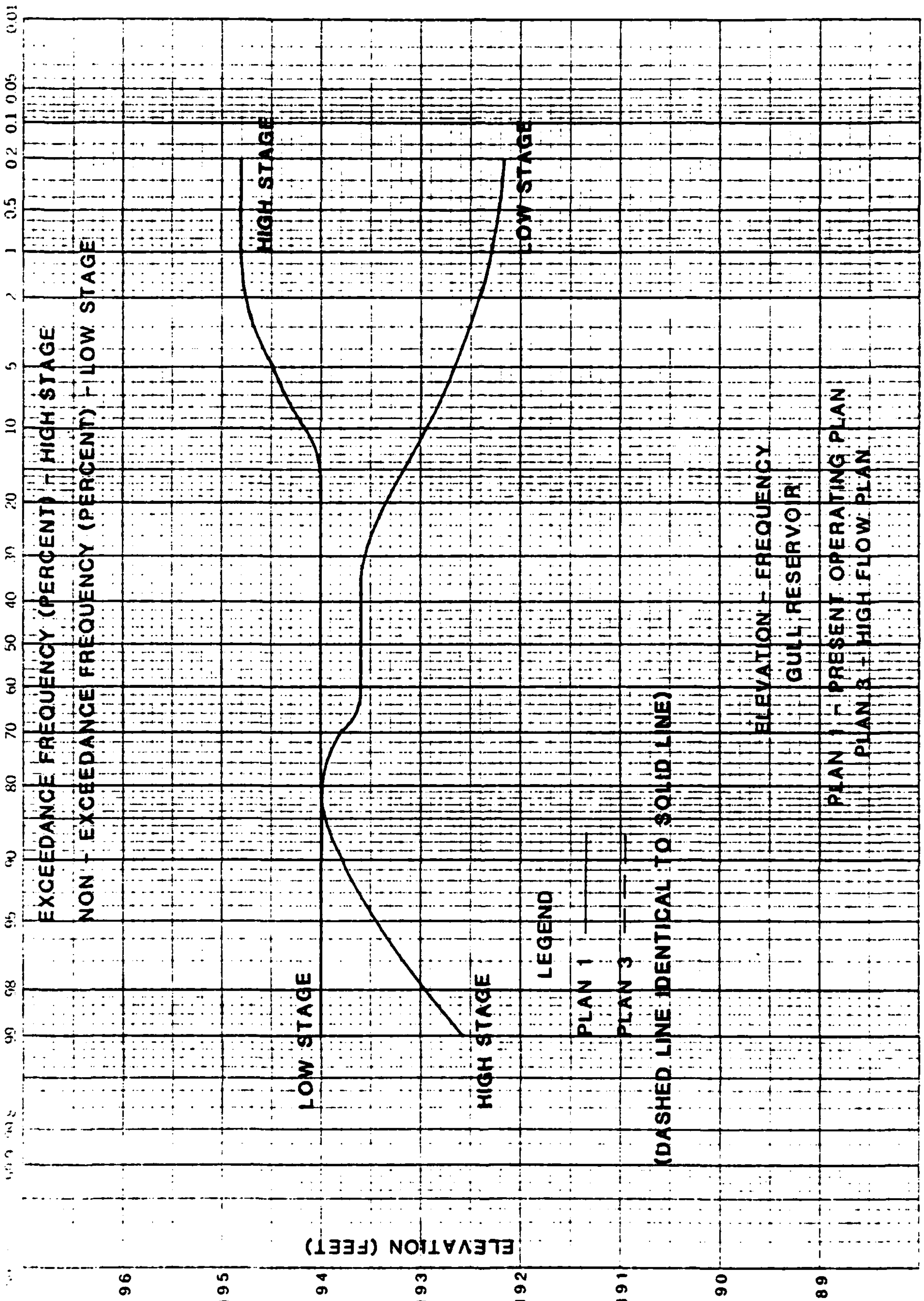
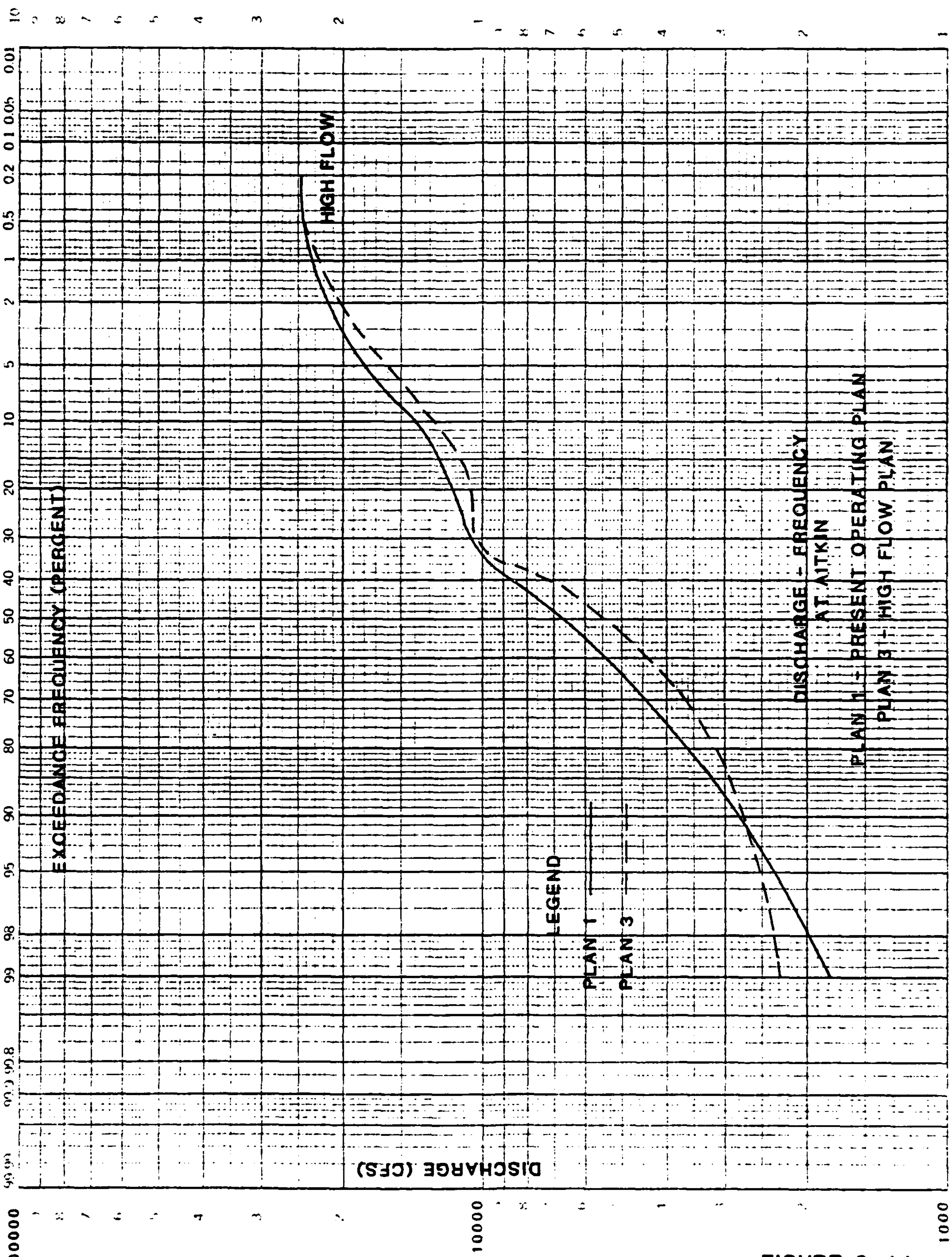

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 3
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
ELEVATION (FEET)
1232
1230
1228
1226
1224
1222
1220
1218

FIGURE 6-9



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
ELEVATION (FEET)
1196
1195
1194
1193
1192
1191
1190
1189
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 3
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN

FIGURE 6-10



EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
LEGEND
PLAN 1
PLAN 3
DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
100000
10000
1000

FIGURE 6-11

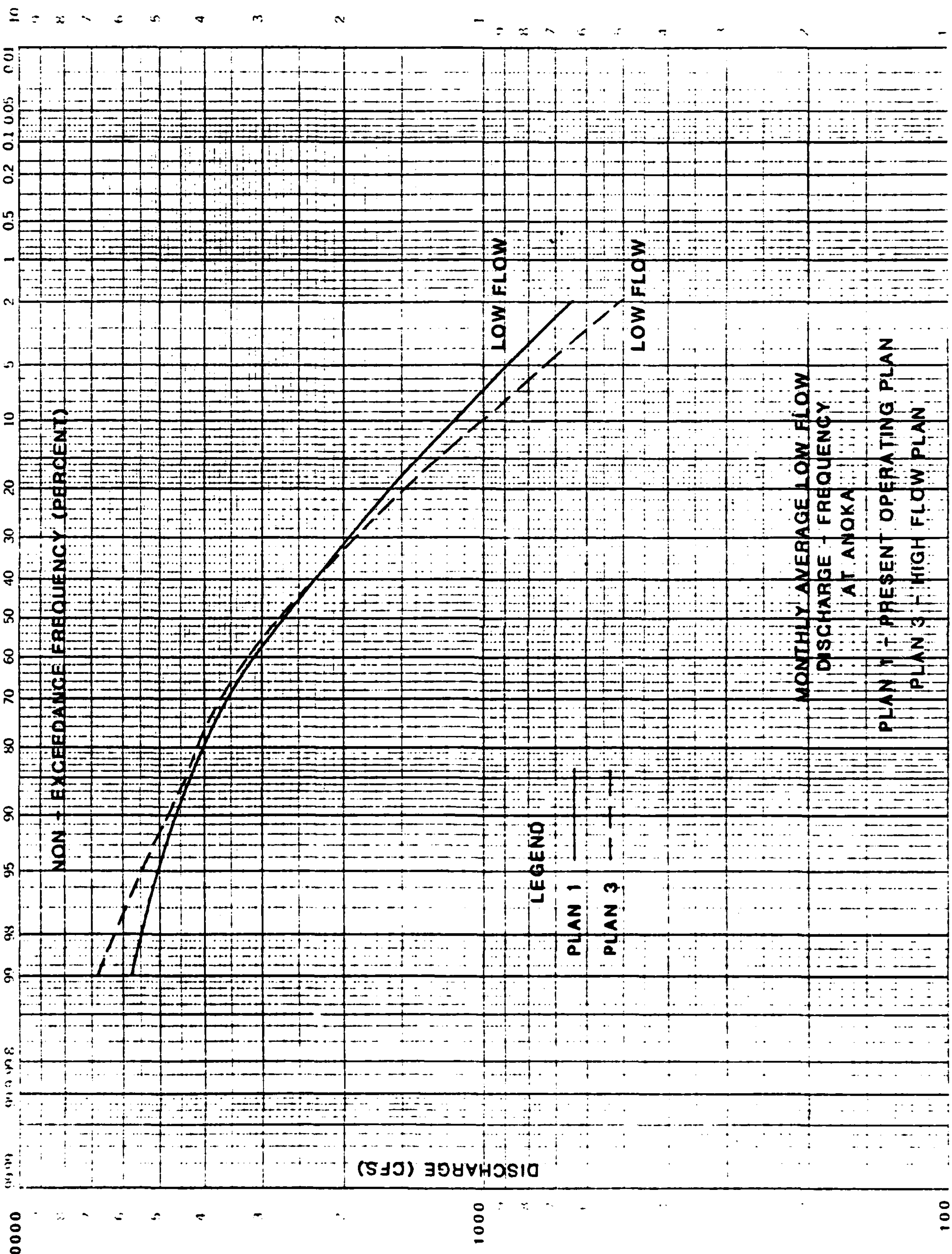

MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 3 - HIGH FLOW PLAN
LEGEND
PLAN 1
PLAN 3
LOW FLOW
LOW FLOW
NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
10000
1000
100
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99

FIGURE 6-12

SECTION 7

PLAN 4 - NATURAL FLOW PLAN

OBJECTIVE

This Plan simulates natural conditions with no dams on the six headwaters lakes.

DISCUSSION

This is a reevaluation of the natural conditions plan evaluated by SAFHL. Similar to the procedure used by SAFHL (see Reference 1, pp. 47 and 51), the simulation at reservoirs is modified to approximate the hydraulic effect of the lakes under their natural, predam, conditions. This is accomplished by setting the reservoir index levels so that the reservoirs are permanently above Level 5. The storage-discharge relationship used above this level is the same relationship that would occur under natural conditions. The simulation follows this curve as the reservoir release logic tries to evacuate the reservoirs back to Level 5, which in essence simulates lake inflow, elevation, and corresponding outflow under natural conditions. A marshy lake existed at the Sandy Reservoir site prior to the construction of the dam and filling of the reservoir. The outflow from this natural lake was governed by backwater effects from the Mississippi River. Therefore, it was decided by the St. Paul District to set Sandy Lake outflows equal to inflows for the natural conditions. Thus, the Sandy Reservoir site was not simulated like a lake for this plan, but all inflows were routed directly down to Libby on the Mississippi River.

RESULTS

Similar to Plans 1 and 3, the Plan 4 results closely approximate the SAFHL natural conditions values after the effect of initial reservoir storage differences are reduced in time.

Hydraulic Results

A summary of annual maximum and minimum elevations at lakes, annual maximum flow at Aitkin and annual minimum flow at Anoka is provided in tables in Appendix H together with a plot of lake elevation versus time for each lake and streamflow at Aitkin and Anoka.

Frequency Results

Frequency relationships based upon the 47 years of simulated record are provided in Figures 7-1 through 7-8 for high stage at lakes, low stage at lakes, high flow at Aitkin, and low flow at Anoka. These results may be misleading when compared with Plan 1. They show the lakes to be at much lower elevations than are observed for Plan 1. This is because the natural lake elevations are much lower than post-dam reservoir levels.

Economic Results

Table 7-1 summarizes economic computations and compares this information to Plan 1, Present Operating Plan. As has been noted, the Natural Flow Plan causes a substantial change in lake elevations as opposed to the elevation levels experienced with the reservoir operation plans. No AAD was calculated for Sandy because of the decision to not model Sandy as a reservoir using HEC-5 (see page 7-1 for discussion). For this same reason no high and low stage data were generated by HEC-5.

The natural Flow Plan total AAD is approximately 3.5 times greater than the Plan 1 total AAD. This is because it was decided by the St. Paul District to use the damage curve data at the lakes based on development conditions with reservoir. This damage data produced much larger AAD than if specific damage curve data would have been developed for natural conditions.

The average annual cost (AAC) of not supplying a minimum of 1600 cfs at ^noka was also calculated for Plan 4, although it was not the explicit purpose of Plan 4 to meet this requirement. However, by calculating the AAC it was then possible to compare Plan 4's average annual net benefit (or cost) relative to Plan 1. The AAC for Plan 4 is $5844.8K compared to $3189.9K for Plan 1. The relative net cost of Plan 4 at Anoka is $2654.9K.

TABLE 7-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 4	PLAN 1
Winnibigoshish		
High Stage	0.0	4.0
Low Stage	90.1	9.7
Total	90.1	13.7
Leech		
High Stage	0.6	11.0
Low Stage	441.9	71.3
Total	442.5	82.3
Pokegama		
High Stage	6.2	25.0
Low Stage	50.2	2.8
Total	56.4	27.8
Sandy		
High Stage	---	29.4
Low Stage	---	2.1
Total	---	31.5
Pine		
High Stage	0.0	16.6
Low Stage	618.8	6.3
Total	618.8	22.9
Gull		
High Stage	72.8	127.5
Low Stage	426.0	15.2
Total	498.8	142.7
Aitkin		
High Flow	469.5	281.3
TOTAL AAD	2,176.1	602.2
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	5844.8	3,189.9

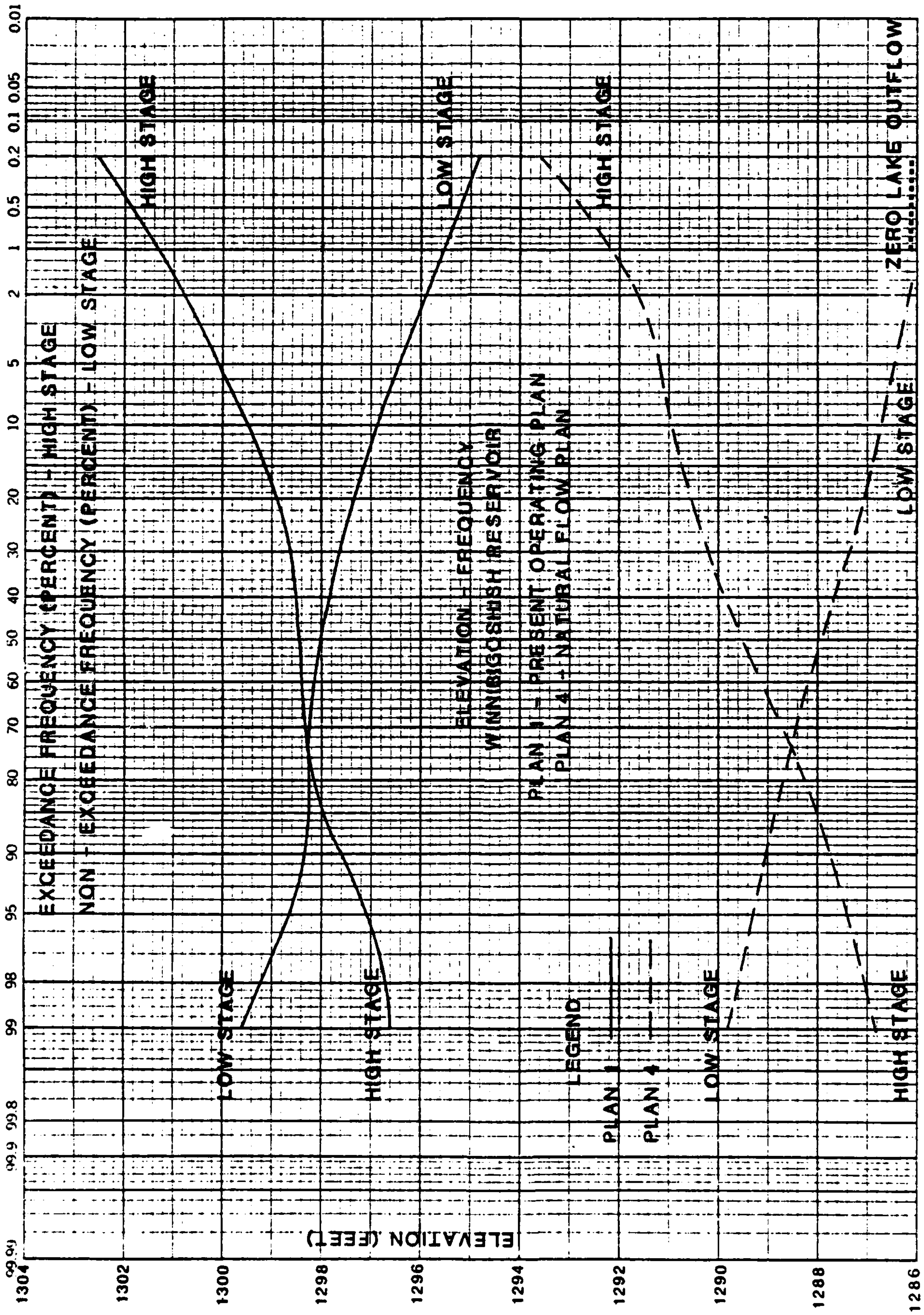

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN
LEGEND
PLAN 1
PLAN 4
HIGH STAGE
LOW STAGE
ZERO LAKE OUTFLOW
ELEVATION (FEET)
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
1304 1302 1300 1298 1296 1294 1292 1290 1288 1286

FIGURE 7-1

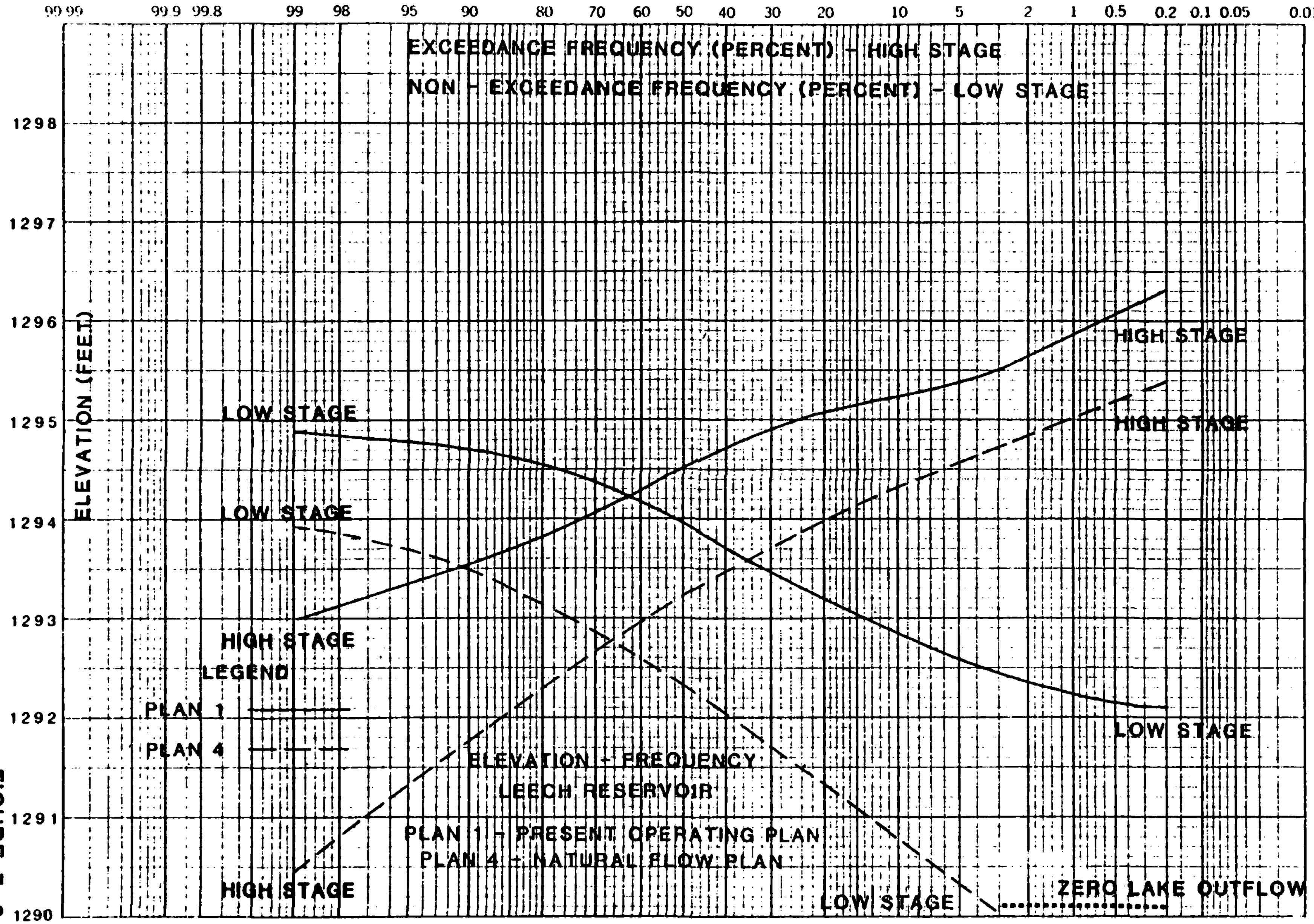

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1298
1297
1296
1295
1294
1293
1292
1291
1290
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
ZERO LAKE OUTFLOW
LEGEND
PLAN 1
PLAN 4
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN

FIGURE 7-2

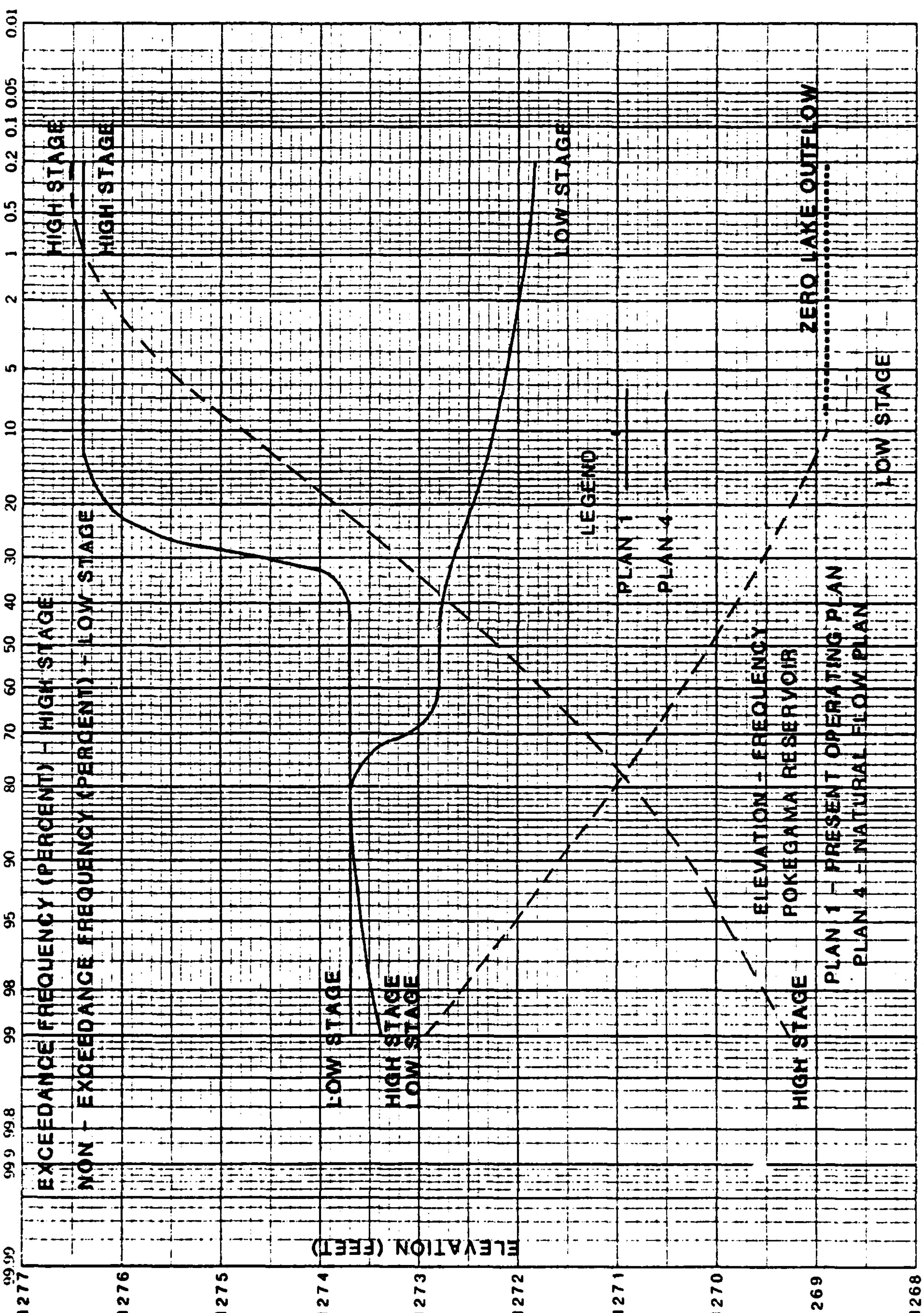
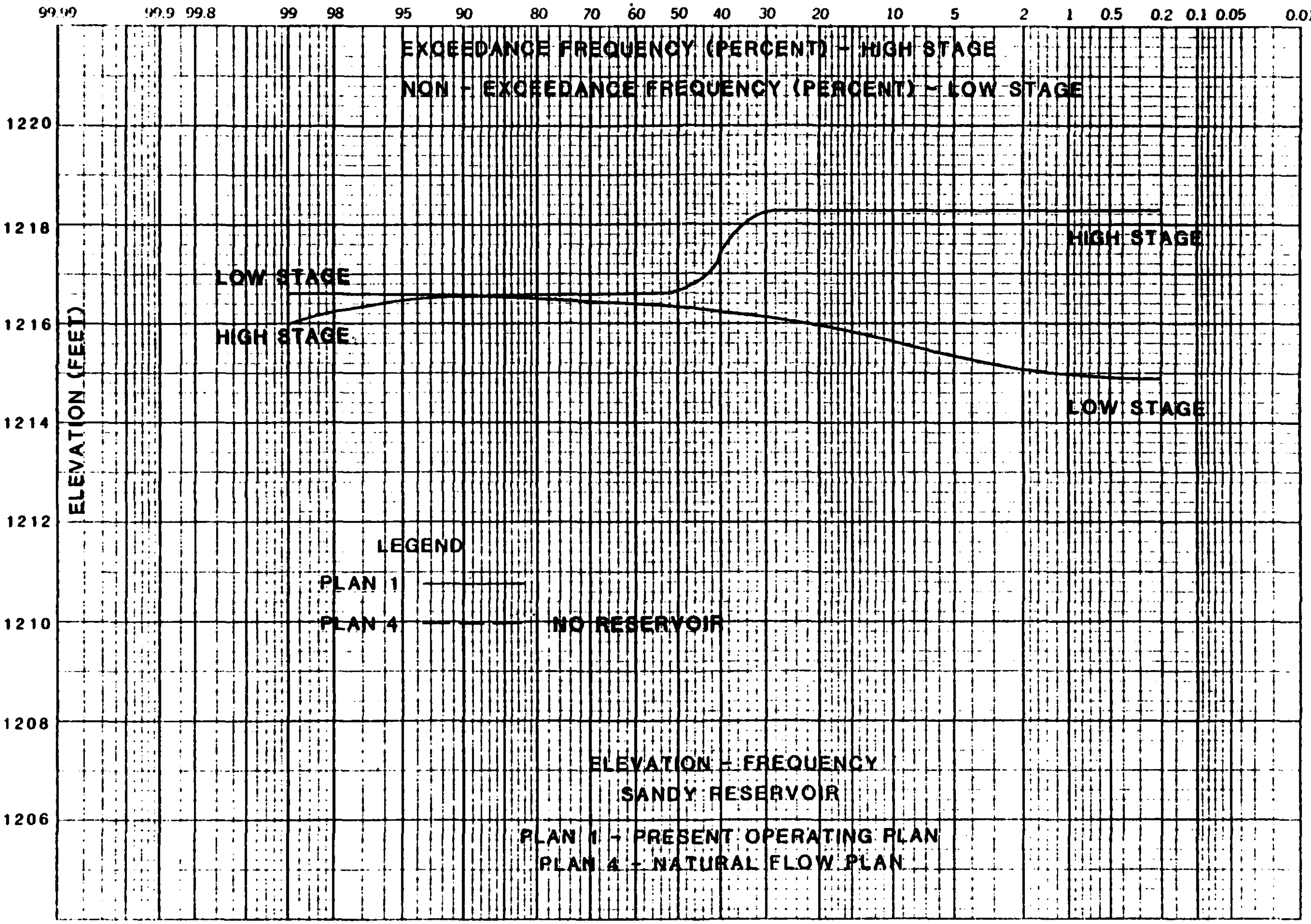
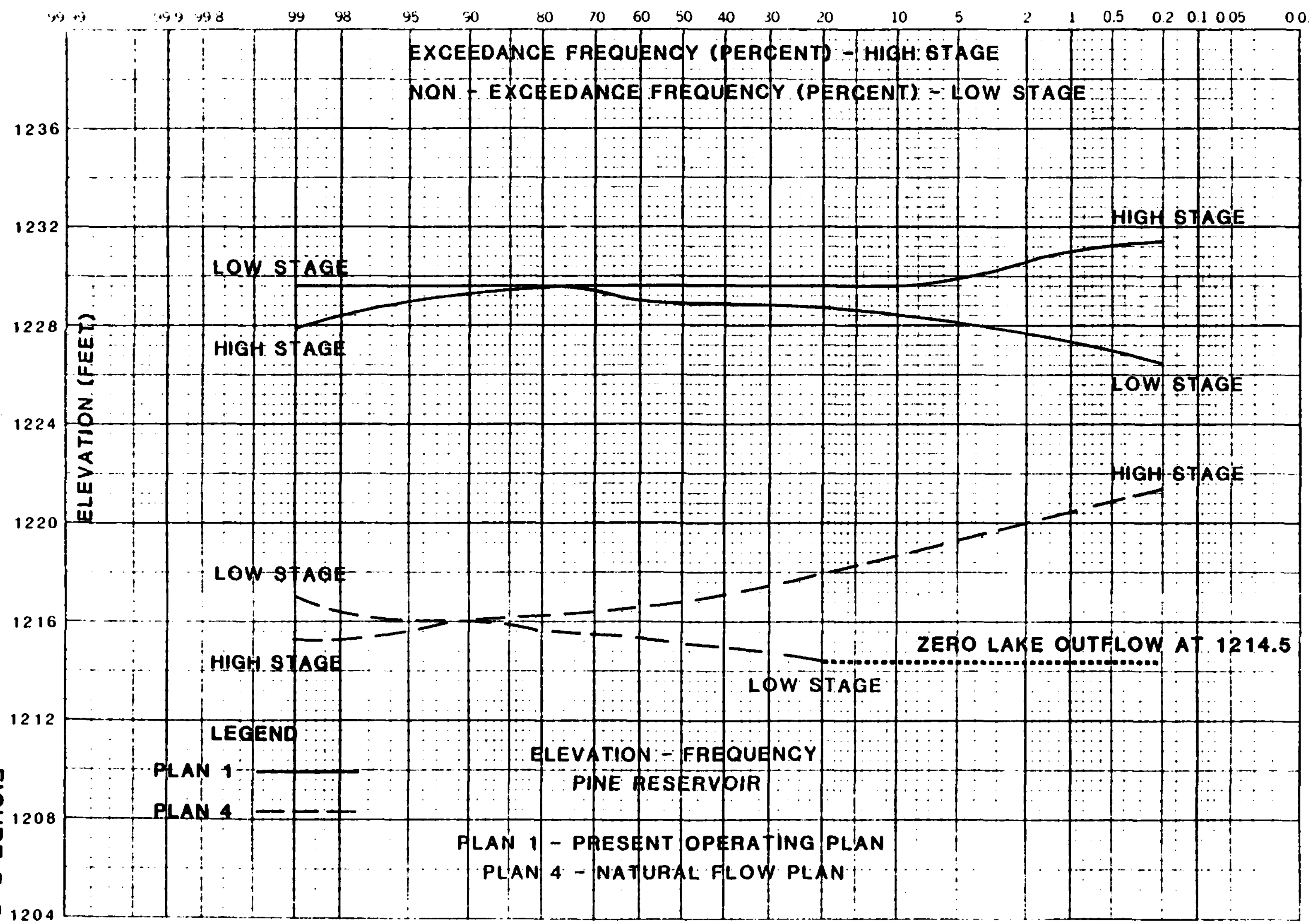

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
ELEVATION (FEET)
1277
1276
1275
1274
1273
1272
1271
1270
1269
1268
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
ZERO LAKE OUTFLOW
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 4
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN

FIGURE 7-3



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
ELEVATION (FEET)
1220
1218
1216
1214
1212
1210
1208
1206
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 4
NO RESERVOIR
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN

FIGURE 7-4



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1236
1232
1228
1224
1220
1216
1212
1208
1204
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
HIGH STAGE
ZERO LAKE OUTFLOW AT 1214.5
LOW STAGE
LEGEND
PLAN 1
PLAN 4
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN

FIGURE 7-5

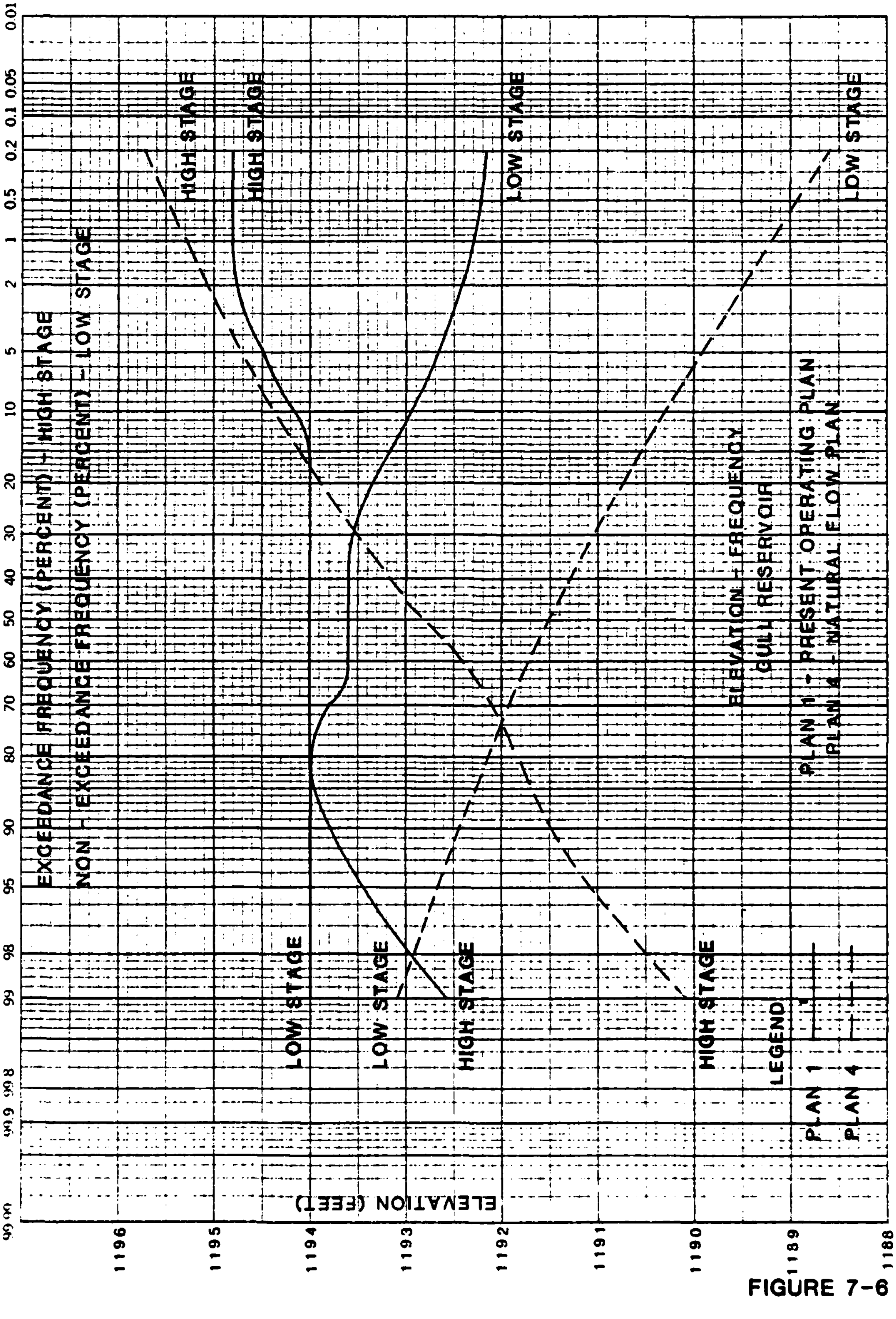

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN
LEGEND
PLAN 1
PLAN 4
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
ELEVATION (FEET)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1196
1195
1194
1193
1192
1191
1190
1189
1188

FIGURE 7-6

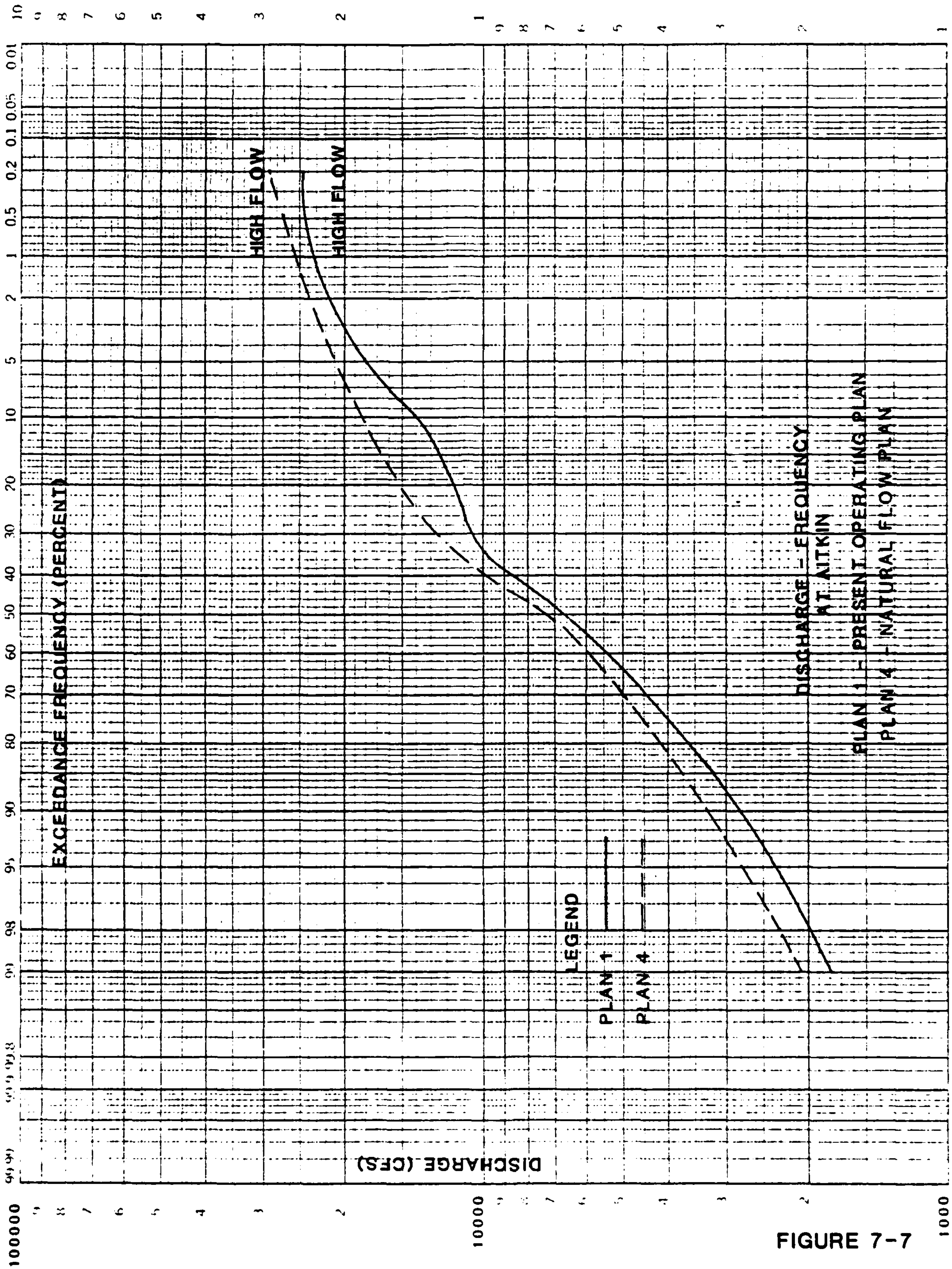

DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN
EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
HIGH FLOW
LEGEND
PLAN 1
PLAN 4
100000
10000
1000

FIGURE 7-7

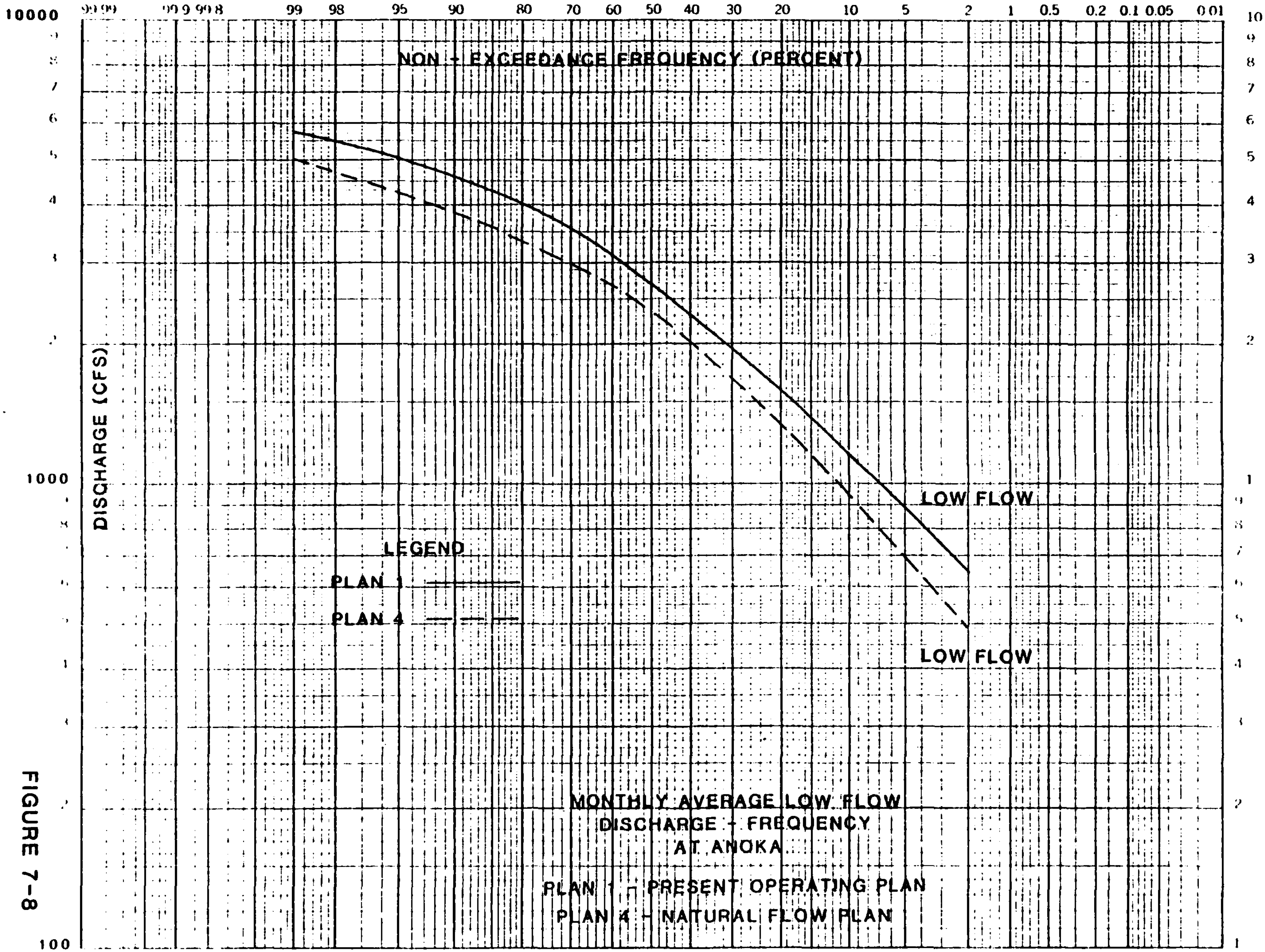

NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
LOW FLOW
LOW FLOW
LEGEND
PLAN 1
PLAN 4
MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 4 - NATURAL FLOW PLAN

FIGURE 7-8

SECTION 8

PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA

OBJECTIVE

This Plan is similar to Plan 1, Present Operating Plan, with the additional objective of maintaining flow at Anoka equal to or greater than 2,275 cfs.

DISCUSSION

This Plan is an alternative to Plan 2, Low Flow Plan, 1,600 cfs at Anoka, with an increased minimum flow requirement. Reservoir operation criteria are identical with the sole exception of Pokegama operation (and corollary effect at Winnibigoshish and Leech) to satisfy the 2,275 cfs requirement at Anoka rather than 1,600 cfs.

RESULTS

During the 47 years of simulation, water shortages occur at Anoka in 37 out of 564 months, 7 percent of the total period. These shortages occur in the following years:

1930, 1932, 1933, 1934, 1935, 1936, 1937, 1938, 1940, and 1976.

As noted in the discussion of the Plan 2 results (Section 5), a problem in HEC-5 caused the reservoirs to not operate properly to meet the minimum flow requirement at Anoka under certain conditions. It is difficult to ascertain the number or magnitude of the shortages which result from this problem. However, a brief review of the months in which shortages occur shows that for 28 of the 37 months, the storage at both Winnibigoshish and Leech is above Level 1 and more water can be released to at least partially meet the minimum flow demand of 2,275 cfs at Anoka. Obvious shortages occur during the months of September-October 1933 and August 1934 through February 1935, and these shortages will still be present when HEC-5 is operating correctly.

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin and annual minimum flow at Anoka is provided in the tables in Appendix I in addition to a plot of reservoir elevation versus time for each reservoir and streamflow at Aitkin and Anoka. It should be noted that these tables and plots include the results

of the HEC-5 problem previously mentioned. The annual minimum elevations for Winnibigoshish and Leech should be lower and the annual minimum flows at Anoka higher for many of the infrequent events (periods of drought).

Frequency Results

Frequency relationships based upon the 47 years of simulated record are provided in Figures 8-1 through 8-8 for high stage at reservoirs, low stage at reservoirs, high flow at Aitkin, and low flow at Anoka. As with the hydraulic results discussed above, one should look at the frequency results with the idea in mind that these results are affected by the problem in HEC-5.

Economic Results

Table 8-1 summarizes economic computations and compares this information to Plan 1, Present Operating Plan. The cost associated with water shortage at Anoka for Plan 1 has been modified to reflect the 2,275 cfs low flow requirement to provide an appropriate base value for comparison with Plan 5. Additional low stage damages result at Winnibigoshish, Leech, and Pokegama Reservoirs in trying to at least partially meet the low flow requirement of 2,275 cfs when compared to Plan 1. This increases the total AAD from $599.5K (Plan 1) to $697.3K (Plan 5). The Plan 5 total AAD will be even larger if the HEC-5 problem is corrected and this plan restudied. Lower minimum elevations at Winnibigoshish and Leech will produce larger low stage damages at these two reservoirs. The amount of the additional damages is difficult to estimate. However, they should be more than compensated for by the decrease in average annual cost of not supplying 2,275 cfs at Anoka during low flow periods. With the HEC-5 problem, the Plan 5 average annual cost at Anoka is $6,495.4K compared to $12,529.7K for Plan 1 including the 2,275 cfs requirement. This produces a relative net benefit of $6,034.3K.

TABLE 8-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 5	PLAN 1
Winnibigoshish		
High Stage	4.0	4.0
Low Stage	28.0	9.7
Total	32.0	13.7
Leech		
High Stage	10.6	11.0
Low Stage	141.0	71.3
Total	151.6	82.3
Pokegama		
High Stage	25.4	25.0
Low Stage	12.6	2.8
Total	38.0	27.8
Sandy		
High Stage	29.4	29.4
Low Stage	2.1	2.1
Total	31.5	31.5
Pine		
High Stage	16.6	16.6
Low Stage	6.3	6.3
Total	22.9	22.9
Gull		
High Stage	127.5	127.5
Low Stage	15.2	15.2
Total	142.7	142.7
Aitkin		
High Flow	278.6	278.6
TOTAL AAD	697.3	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 2,275 cfs)		
Anoka		
Low Flow	6,495.4	12,529.7

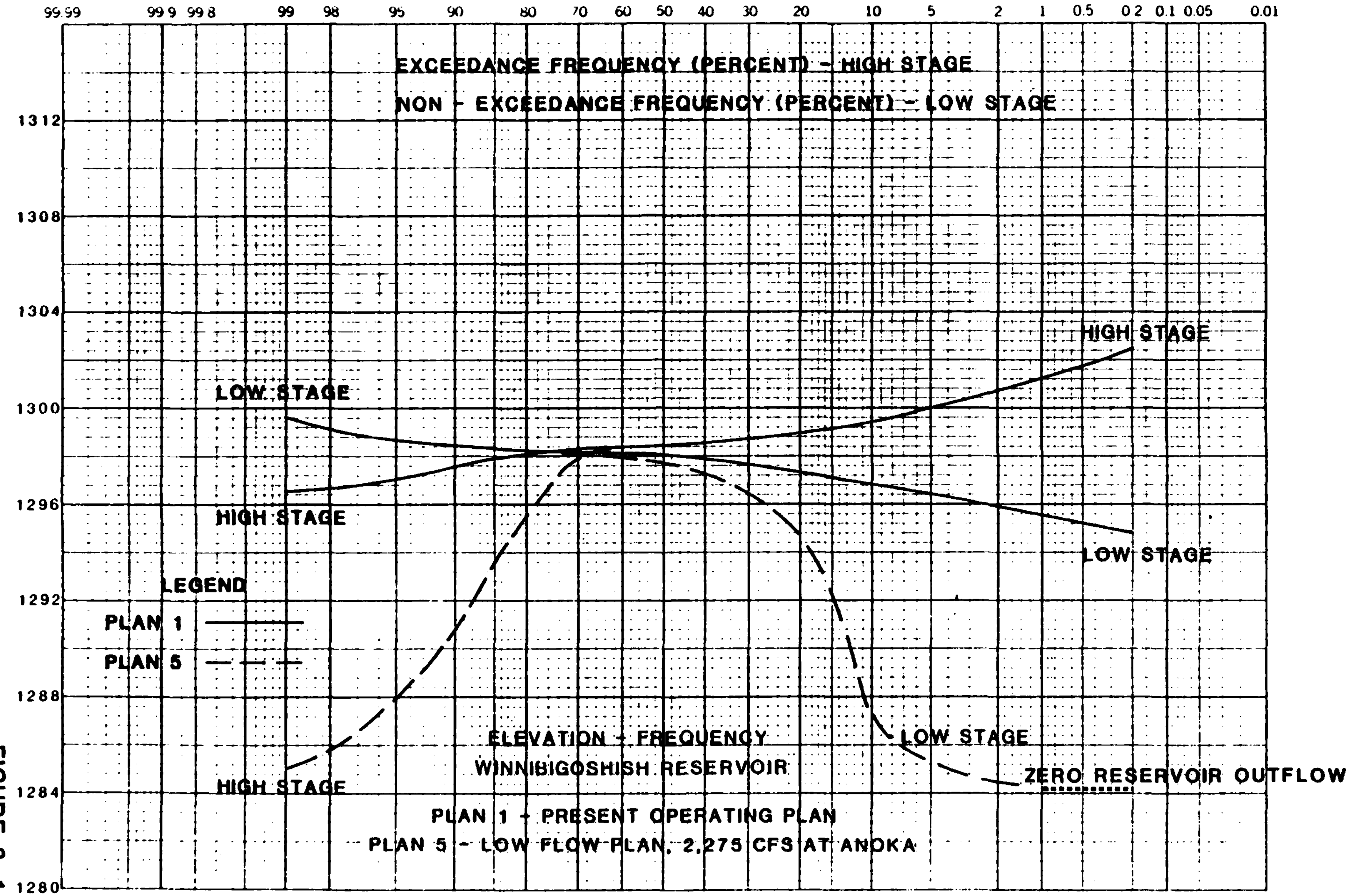
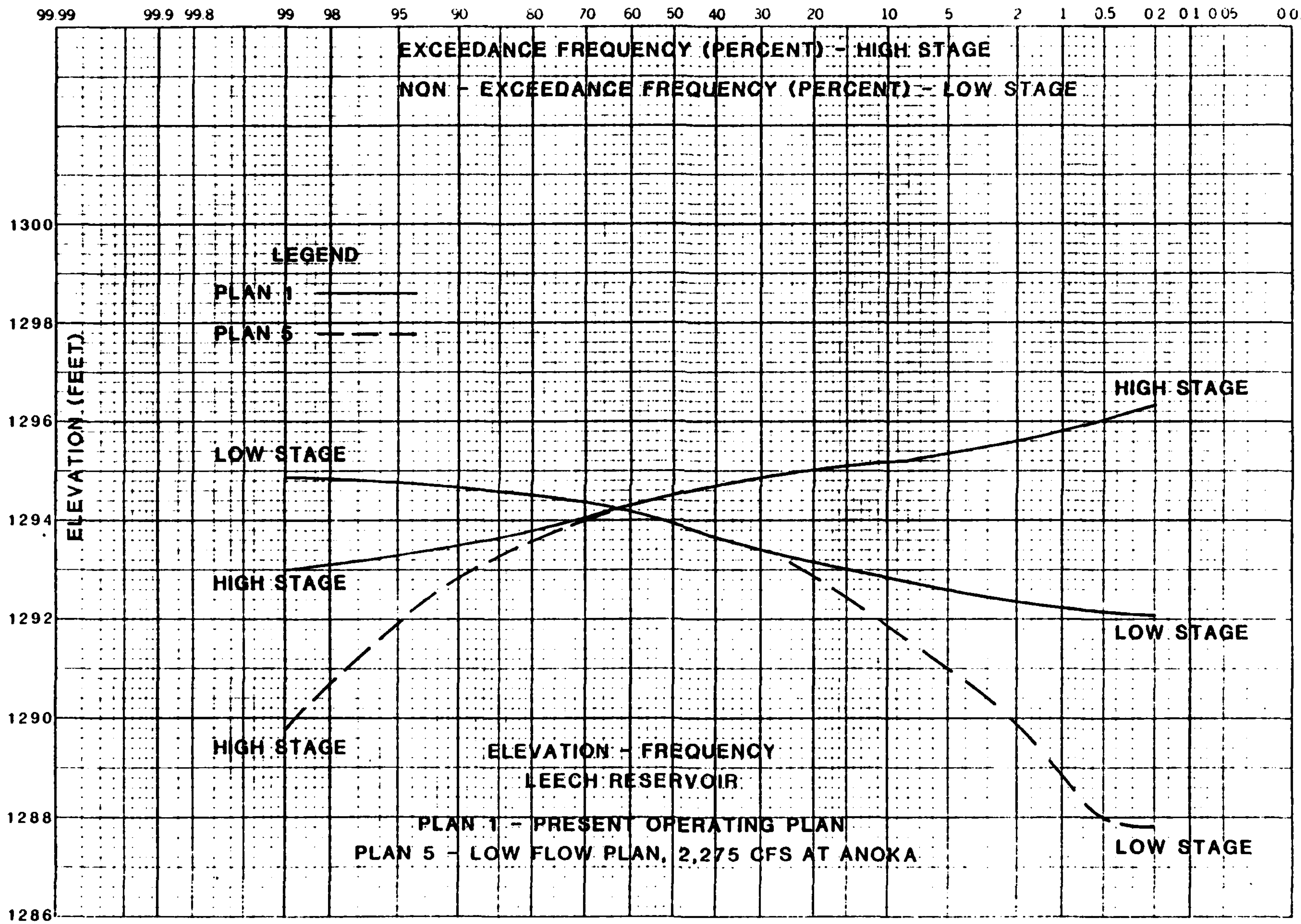

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1312
1308
1304
1300
1296
1292
1288
1284
1280
HIGH STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 5
LOW STAGE
ZERO RESERVOIR OUTFLOW
HIGH STAGE
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA

FIGURE 8-1



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
ELEVATION (FEET)
1300
1298
1296
1294
1292
1290
1288
1286
LEGEND
PLAN 1
PLAN 5
HIGH STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA

FIGURE 8-2

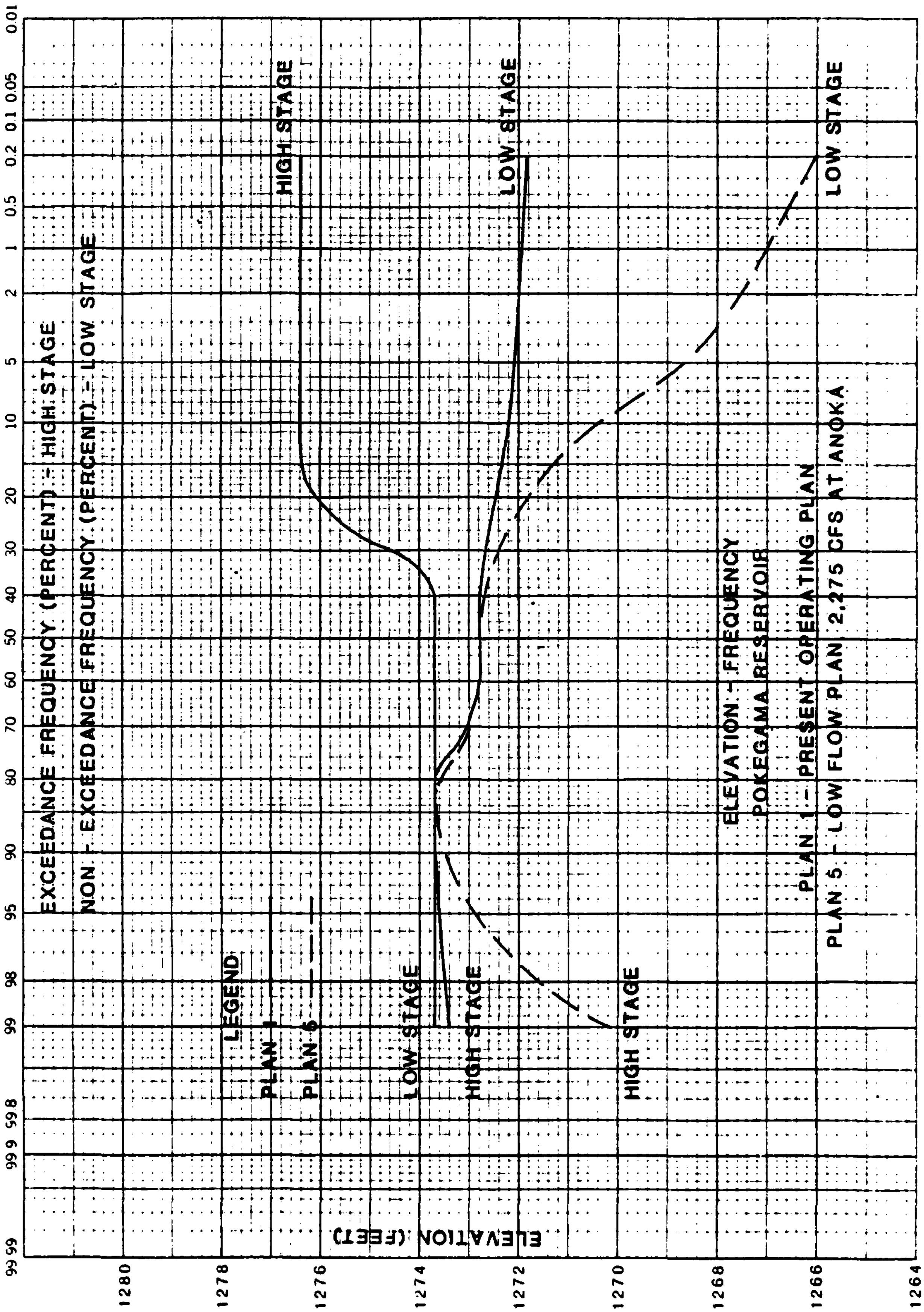

ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN 2,275 CFS AT ANOKA
EXCEEDANCE FREQUENCY (PERCENT) = HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) = LOW STAGE
LEGEND
PLAN 1
PLAN 5
HIGH STAGE
LOW STAGE
ELEVATION (FEET)
1280
1278
1276
1274
1272
1270
1268
1266
1264
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

FIGURE 8-3

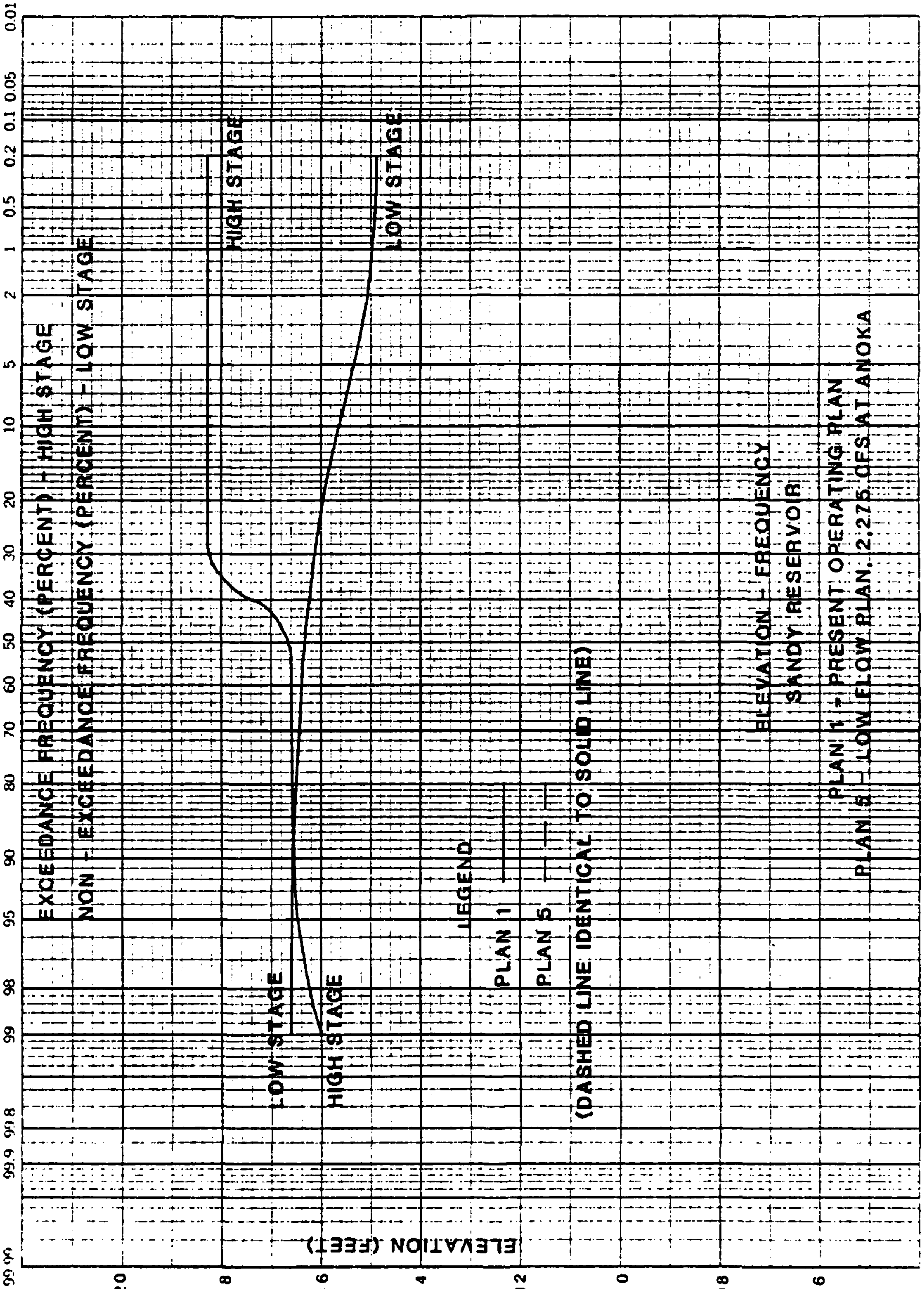

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1220
1218
1216
1214
1212
1210
1208
1206
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 5
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA

FIGURE 8-4

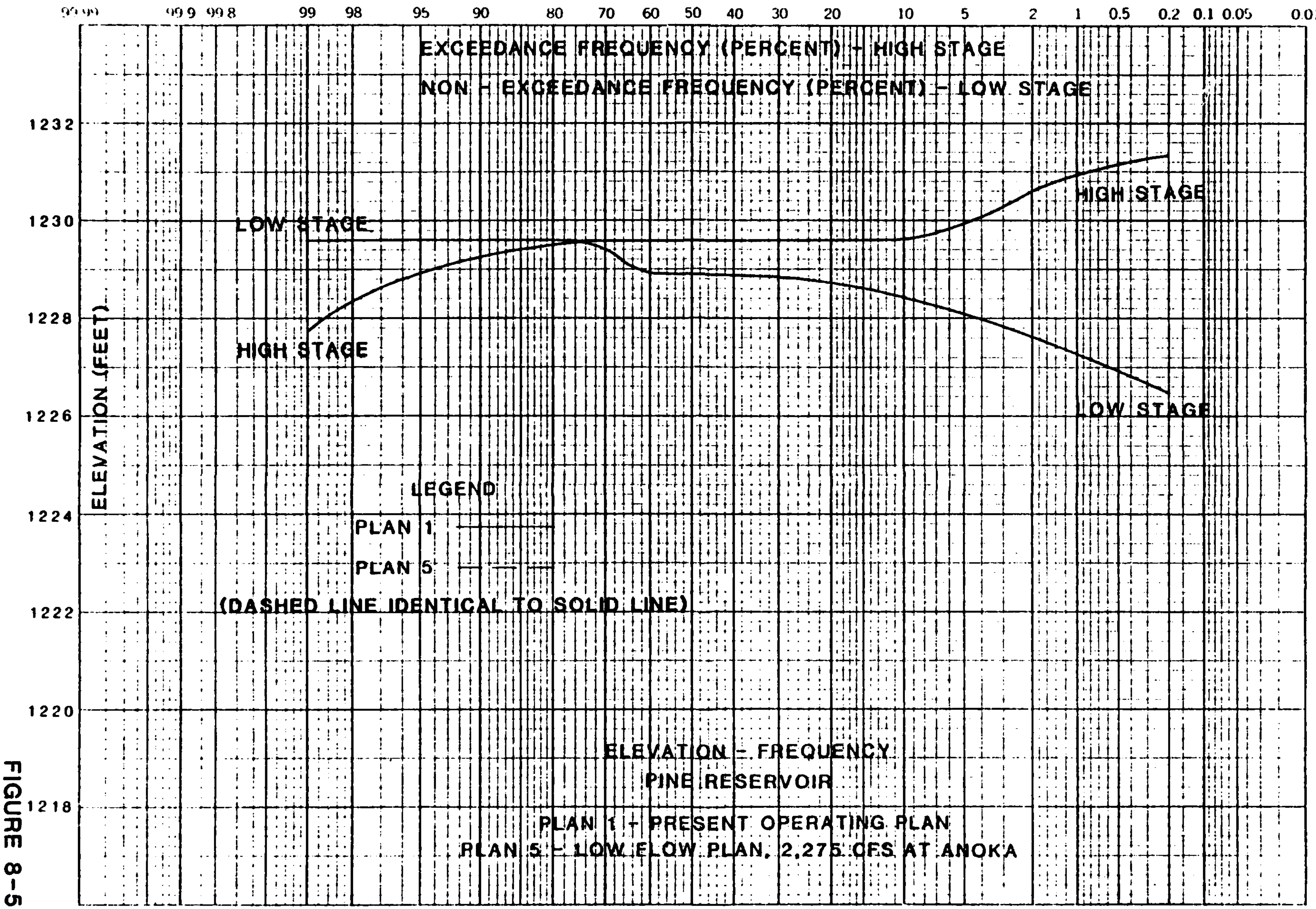

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
1232
1230
1228
1226
1224
1222
1220
1218
ELEVATION (FEET)
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 5
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA

FIGURE 8-5

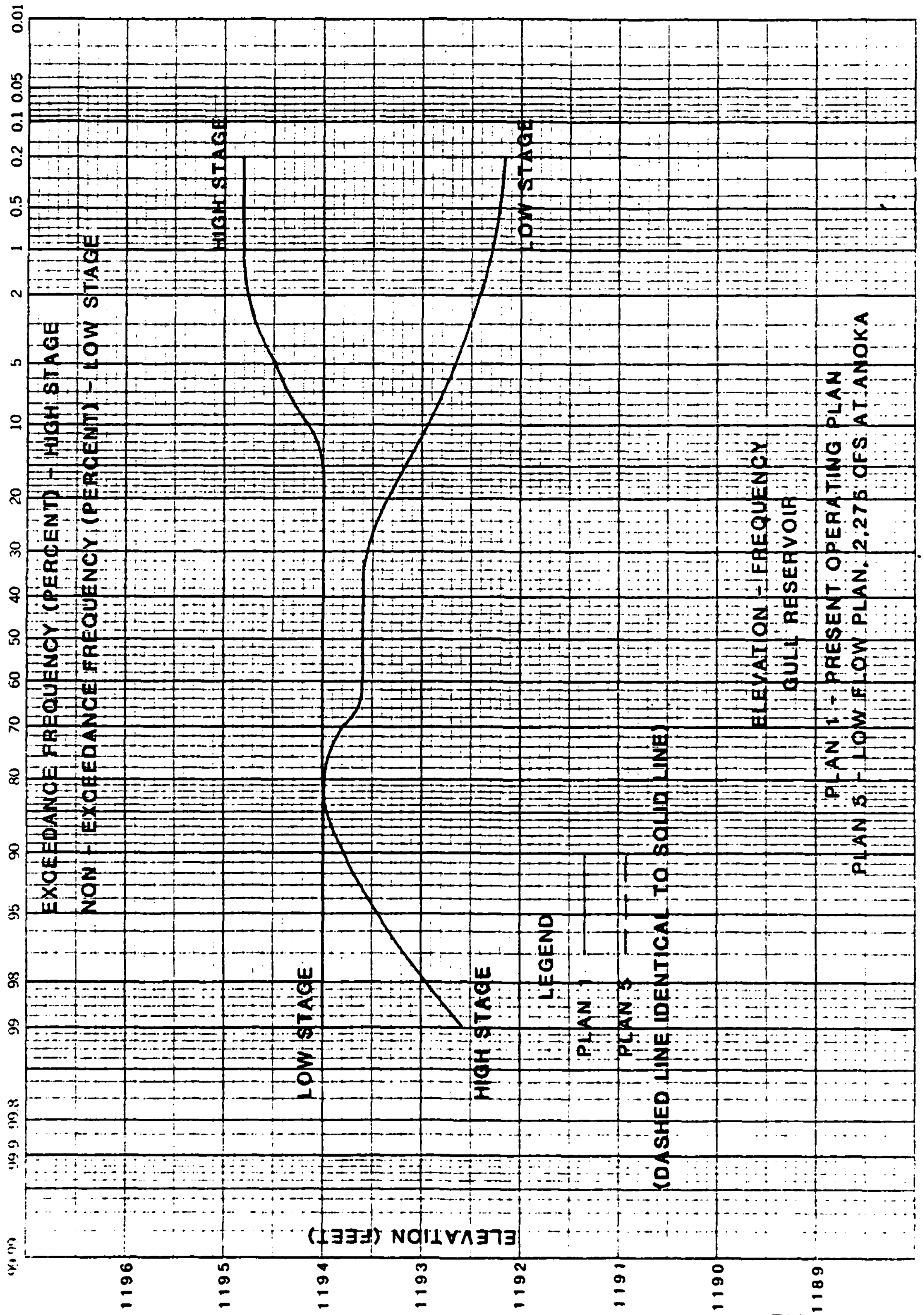

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 5
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1196
1195
1194
1193
1192
1191
1190
1189

FIGURE 8-6

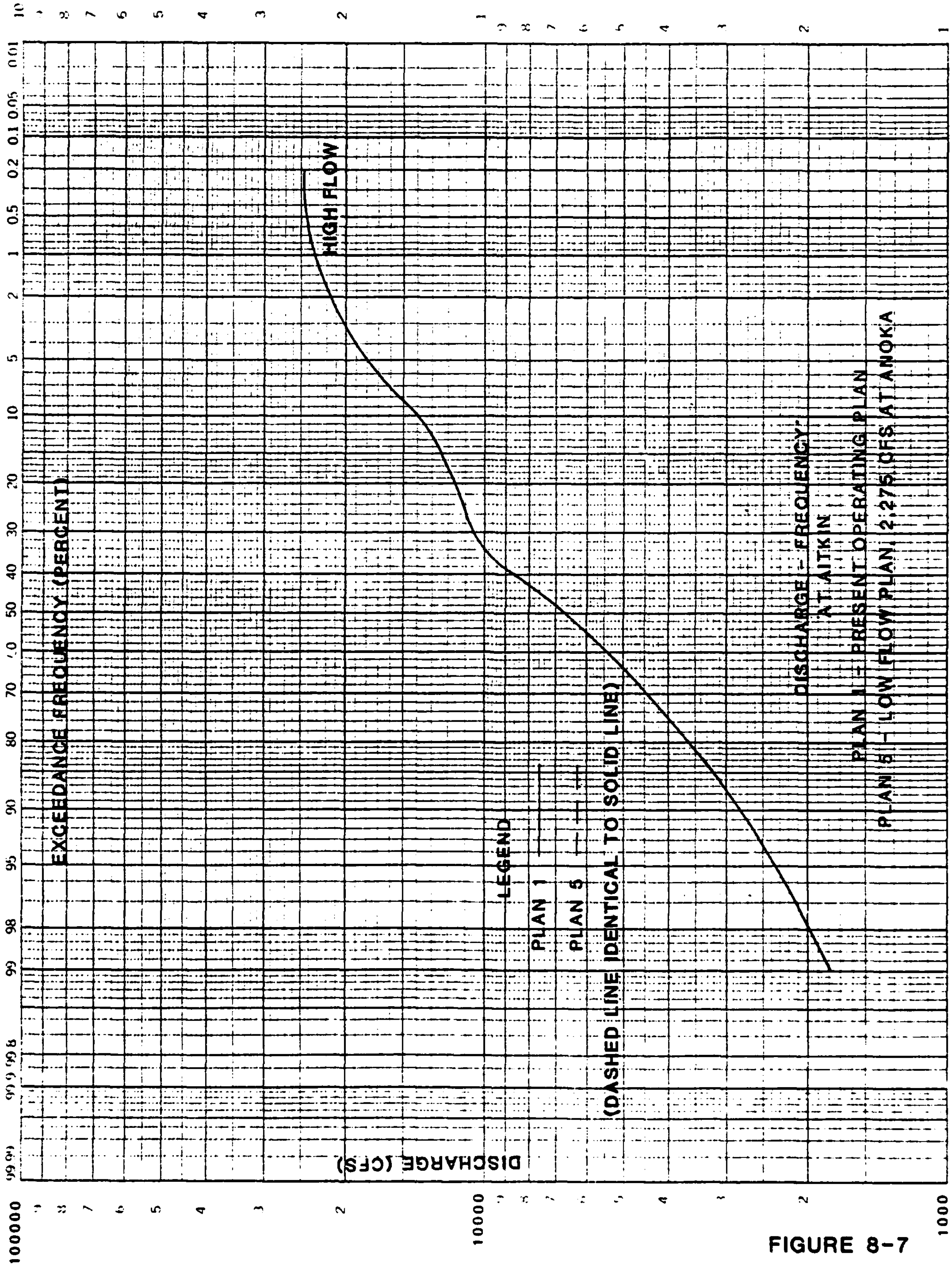
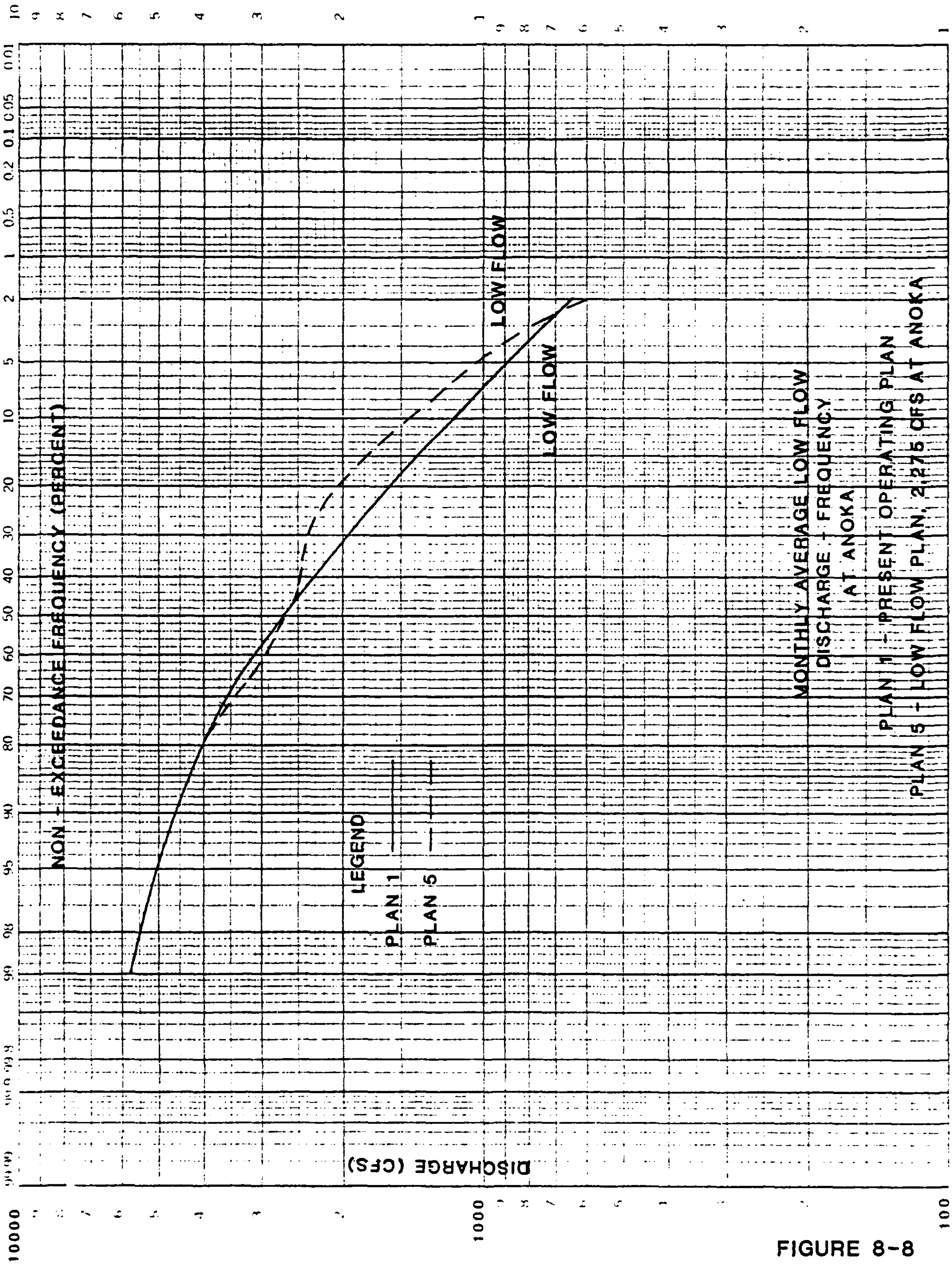

DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA
EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
LEGEND
PLAN 1
PLAN 5
(DASHED LINE IDENTICAL TO SOLID LINE)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
100000
10000
1000

FIGURE 8-7



MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 5 - LOW FLOW PLAN, 2,275 CFS AT ANOKA
LEGEND
PLAN 1
PLAN 5
LOW FLOW
LOW FLOW
NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
10000
1000
100

FIGURE 8-8

SECTION 9

PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA

OBJECTIVE

The objective for this Plan is to operate the reservoirs in the most favorable manner possible within the "present operating limits" (see Figure 1-2) in order to maintain flow at Anoka equal to or greater than 4,800 cfs.

DISCUSSION

Based upon the results of Plan 5, it is obvious that the substantially increased low flow requirement at Anoka will be impossible to achieve. For this plan, the reservoir operating criteria were changed at Winnibigoshish, Leech, and Pokegama to provide less drawdown during the winter and spring periods. The revised index levels for these three reservoirs are shown on Figures 9-1 through 9-3, respectively.

RESULTS

During the 564 months of simulation, water shortages occur for 187 months (35 percent of the total period) at Anoka when attempting to meet a minimum flow requirement of 4,800 cfs. Shortages occur in months of every year between 1930 and 1976 except: 1942, 1944, 1946, 1952, 1954, 1966, 1972, 1973, and 1975. The number and size of the shortages are magnified by the HEC-5 problem which does not allow full use of the water available in Winnibigoshish and Leech to attempt to satisfy the Anoka low flow requirement. Because of this relatively high minimum flow requirement of 4,800 cfs, it is infeasible to review all of the water short months to determine in which ones the corrected version of HEC-5 will produce results satisfying the 4,800 cfs Anoka flow need. However, it is expected that the correction will not eliminate most water short months because of the size of the Anoka demand (4,800 cfs).

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin, and annual minimum flow at Anoka is provided in the tables in Appendix J along with a plot of reservoir elevation versus time for each reservoir and streamflow at Aitkin and Anoka.

Frequency Results

Frequency relationships based on the 47 years of simulated record are provided in Figures 9-4 through 9-11 for high and low stage at reservoirs, high flow at Aitkin, and low flow at Anoka. Once again, these results include the effects of the HEC-5 problem. An example of how this problem affects the frequency results can be seen in comparing the Plan 5 and Plan 6 frequency curves for Leech Reservoir (Figures 8-2 and 9-5, respectively). The low stage curve for Plan 6 stays at higher elevations than the Plan 5 curve for exceedance frequencies in the range of 10 to 0.2 percent. One would expect just the opposite, as the Plan 6 Anoka minimum flow requirement of 4,800 cfs should place greater demands on Winnibigoshish, Leech, and Pokegama Reservoirs than the Plan 5 requirement of 2,275 cfs. Analysis of the HEC-5 monthly simulation for Plans 5 and 6 shows that early in the 47-year period of interest that Plan 5 attempts to release enough water from Pokegama to meet Anoka's 2,275 cfs requirement. Plan 6 simulation makes less of an attempt even when Pokegama has additional available water, such as in March 1930. This is incorrect.

The comparison of Anoka low flow curves for Plan 1 and 6 (Figure 9-11) shows that Plan 6 has lower flows than Plan 1 in the range of 50 to 2 percent non-exceedance. These lower low flows are a result of Plan 6 trying to maintain 4,800 cfs at Anoka. When the reservoirs can no longer meet this need they have been drawn down further than in the case of Plan 1 and this further minimizes future available water to release for Anoka. Anoka's flows decrease as a result, as can be seen in the frequency curves for the two plans.

Economic Results

Table 9-1 summarizes economic computations and compares this information to Plan 1, Present Operating Plan. The cost associated with water shortage at Anoka for Plan 1 has been modified to reflect the 4,800 cfs low flow requirement to provide an appropriate base value for comparison with Plan 6. Plan 6, like Plan 5, shows increased low stage damages over Plan 1 at Winnibigoshish, Leech, and Pokegama. The total AAD increases from $599.5K (Plan 1) to $738.8K (Plan 6). The Plan 6 AAD will be larger without the HEC-5 problem. The average annual cost for not supplying Anoka with 4,800 cfs is $109,730.4K for Plan 6 compared to $122,582.5K for Plan 1. This is a net benefit increase of $12,852.1K for Plan 6 relative to Plan 1.

TABLE 9-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 6	PLAN 1
Winnibigoshish		
High Stage	1.9	4.0
Low Stage	46.1	9.7
Total	48.0	13.7
Leech		
High Stage	12.3	11.0
Low Stage	150.2	71.3
Total	162.5	82.3
Pokegama		
High Stage	23.7	25.0
Low Stage	29.8	2.8
Total	53.5	27.8
Sandy		
High Stage	29.4	29.4
Low Stage	2.1	2.1
Total	31.5	31.5
Pine		
High Stage	16.6	16.6
Low Stage	6.3	6.3
Total	22.9	22.9
Gull		
High Stage	127.5	127.5
Low Stage	15.2	15.2
Total	142.7	142.7
Aitkin		
High Flow	277.7	278.6
TOTAL AAD	738.8	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 4,800 cfs)		
Anoka		
Low Flow	109,730.4	122,582.5

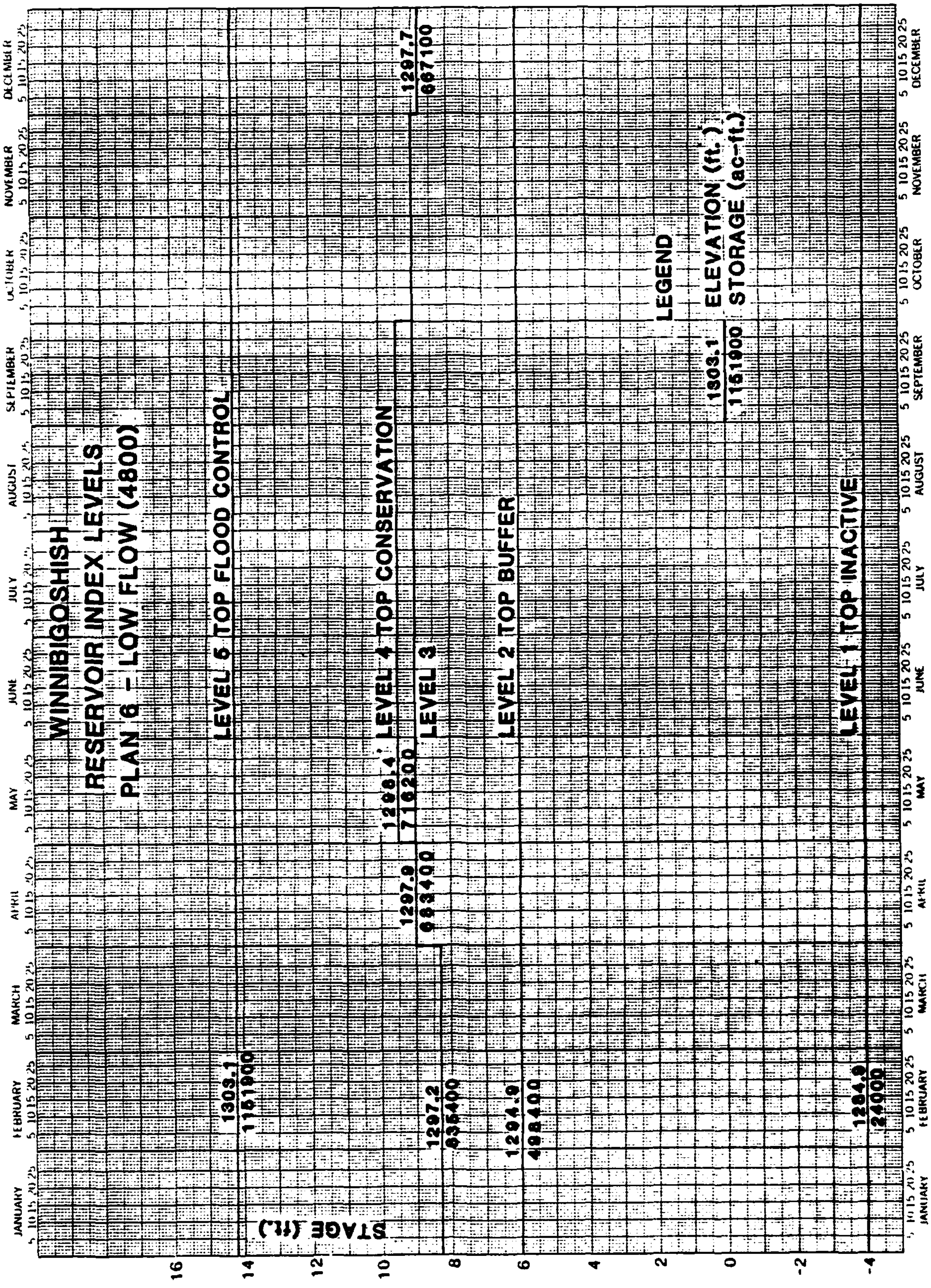

WINNIBIGOSHISH
RESERVOIR INDEX LEVELS
PLAN 6 - LOW FLOW (4800)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
1303.1
1151900
1297.2
635400
1294.9
498400
1284.9
24000
1297.9
683400
1298.4
716200
1303.1
1151900
1297.7
667100
STAGE (ft.)
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25

FIGURE 9-1

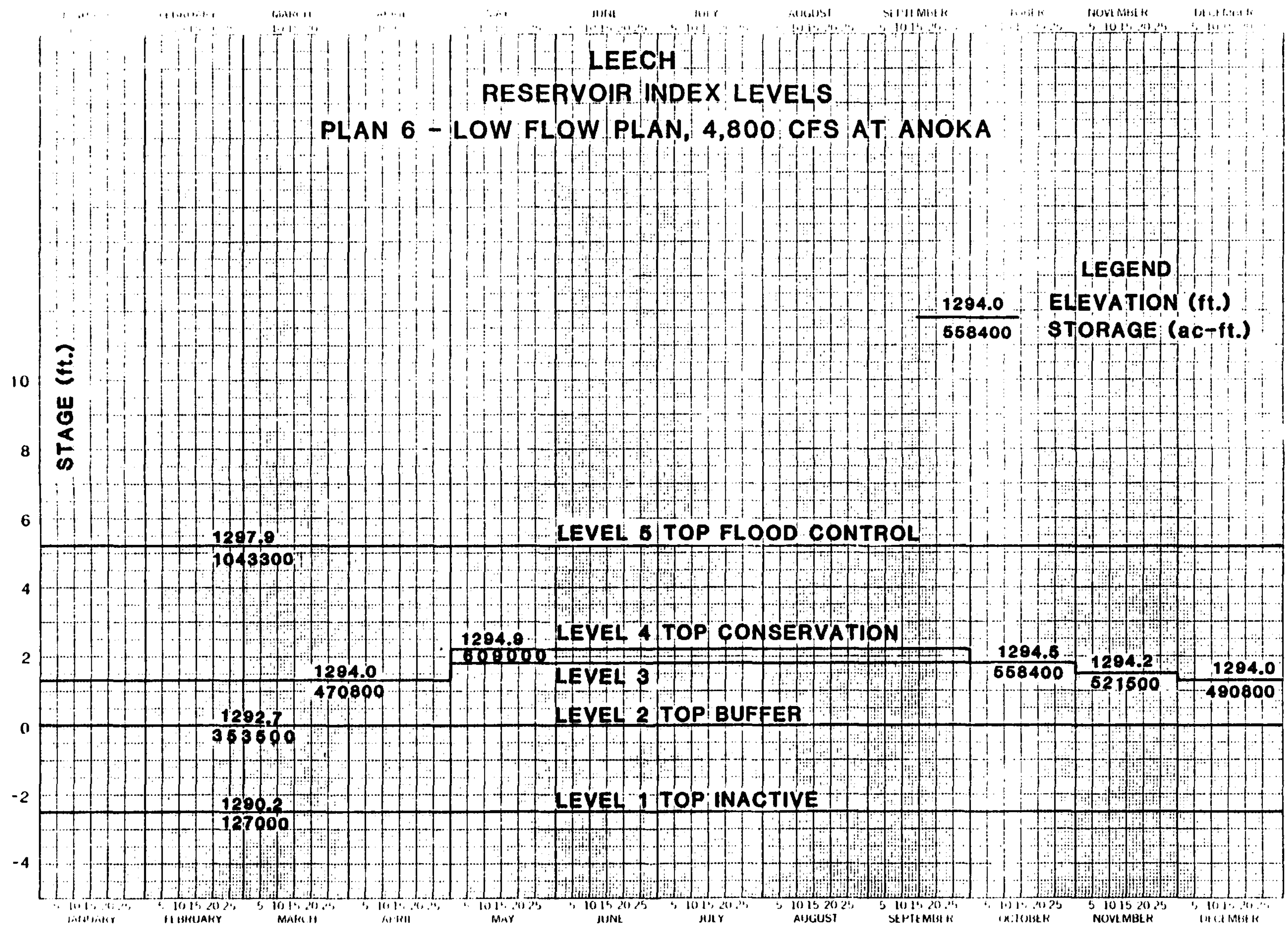

LEECH
RESERVOIR INDEX LEVELS
PLAN 6 – LOW FLOW PLAN, 4,800 CFS AT ANOKA
LEGEND
1294.0
558400
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
10
8
6
4
2
0
-2
-4
LEVEL 5 TOP FLOOD CONTROL
1297.9
1043300
LEVEL 4 TOP CONSERVATION
1294.9
609000
LEVEL 3
1294.0
470800
1294.5
558400
1294.2
521500
1294.0
490800
LEVEL 2 TOP BUFFER
1292.7
353500
LEVEL 1 TOP INACTIVE
1290.2
127000
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 9-2

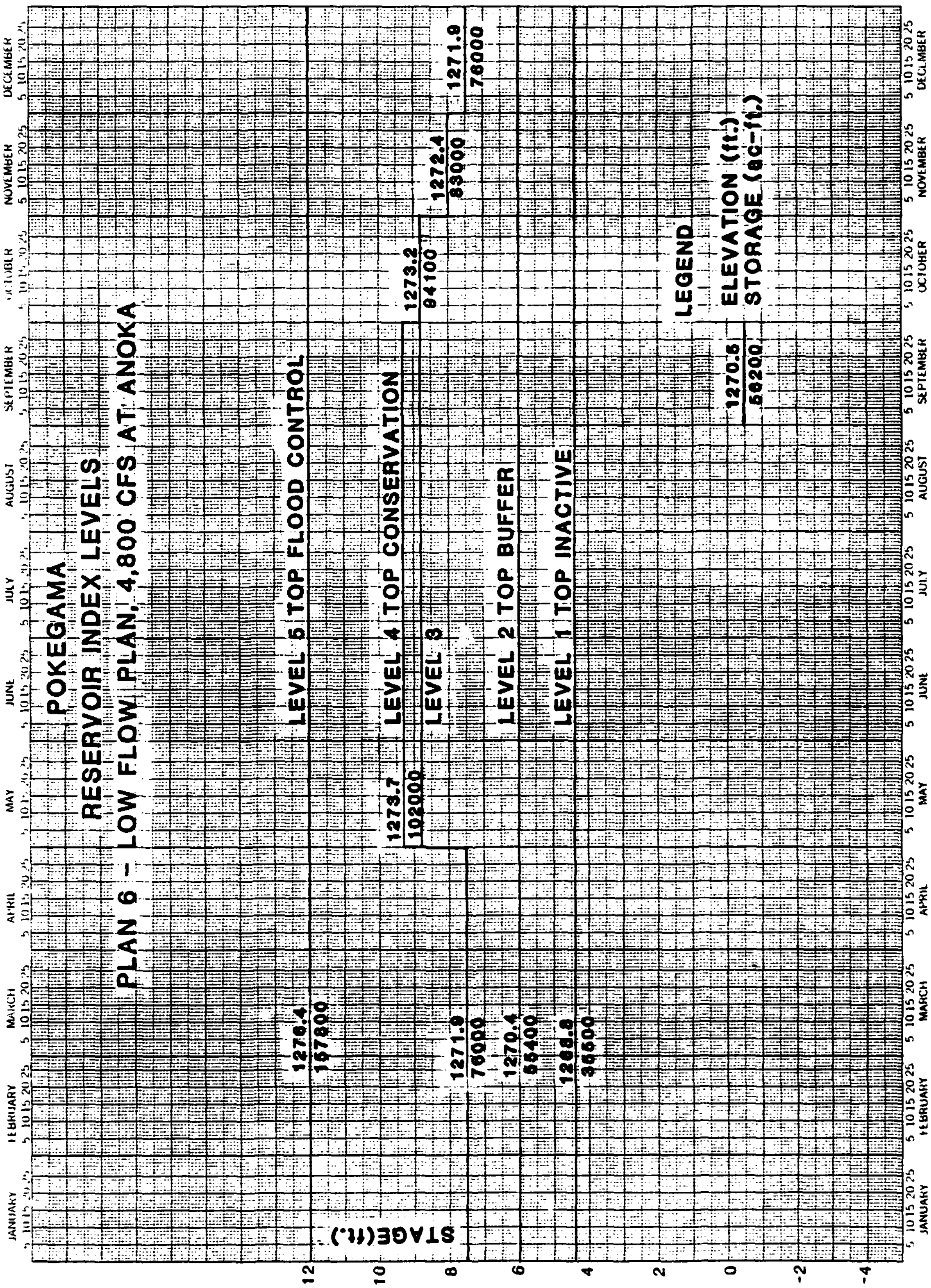
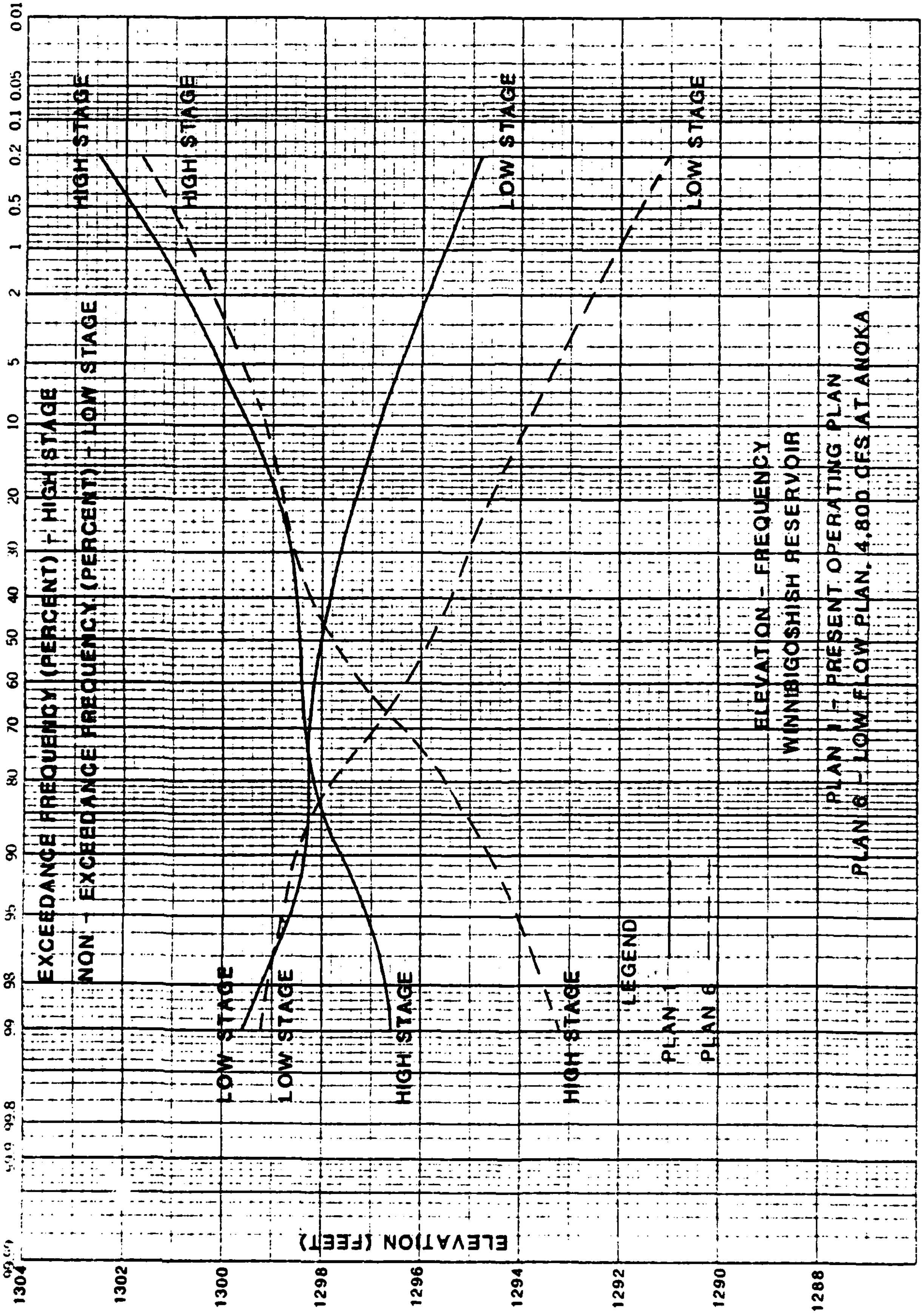
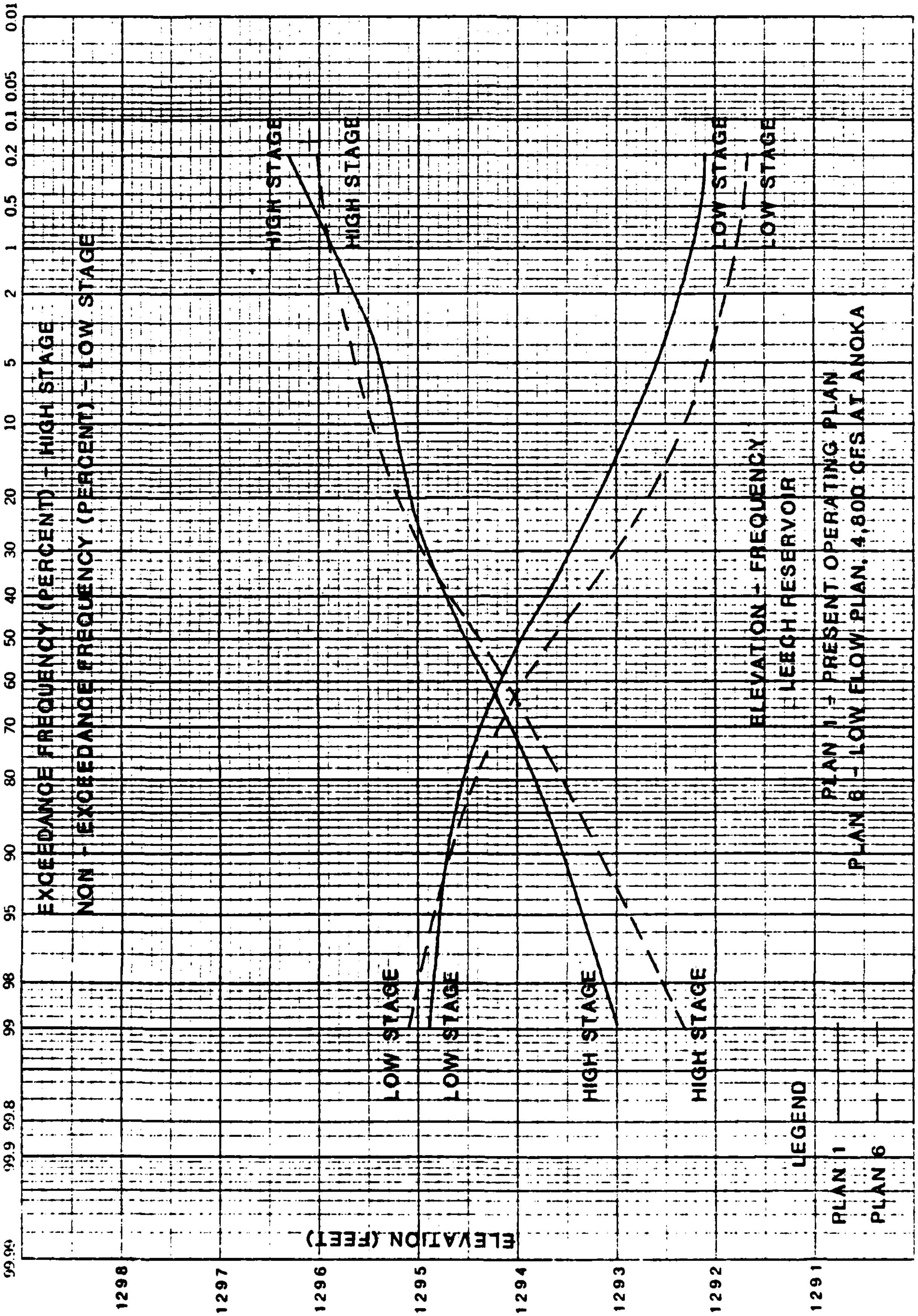

POKEGAMA
RESERVOIR INDEX LEVELS
PLAN 6 – LOW FLOW PLAN, 4,800 CFS AT ANOKA
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1276.4
157800
1271.9
76000
1270.4
56400
1268.8
36500
1273.7
102000
1273.2
94100
1272.4
83000
1271.9
76000
LEGEND
1270.5 ELEVATION (ft.)
56200 STORAGE (ac-ft.)
STAGE(ft.)
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 9-3



ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
LEGEND
PLAN 1
PLAN 6
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
ELEVATION (FEET)
1304
1302
1300
1298
1296
1294
1292
1290
1288
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8

FIGURE 9-4



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
ELEVATION (FEET)
1298
1297
1296
1295
1294
1293
1292
1291
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA
LEGEND
PLAN 1
PLAN 6

FIGURE 9-5

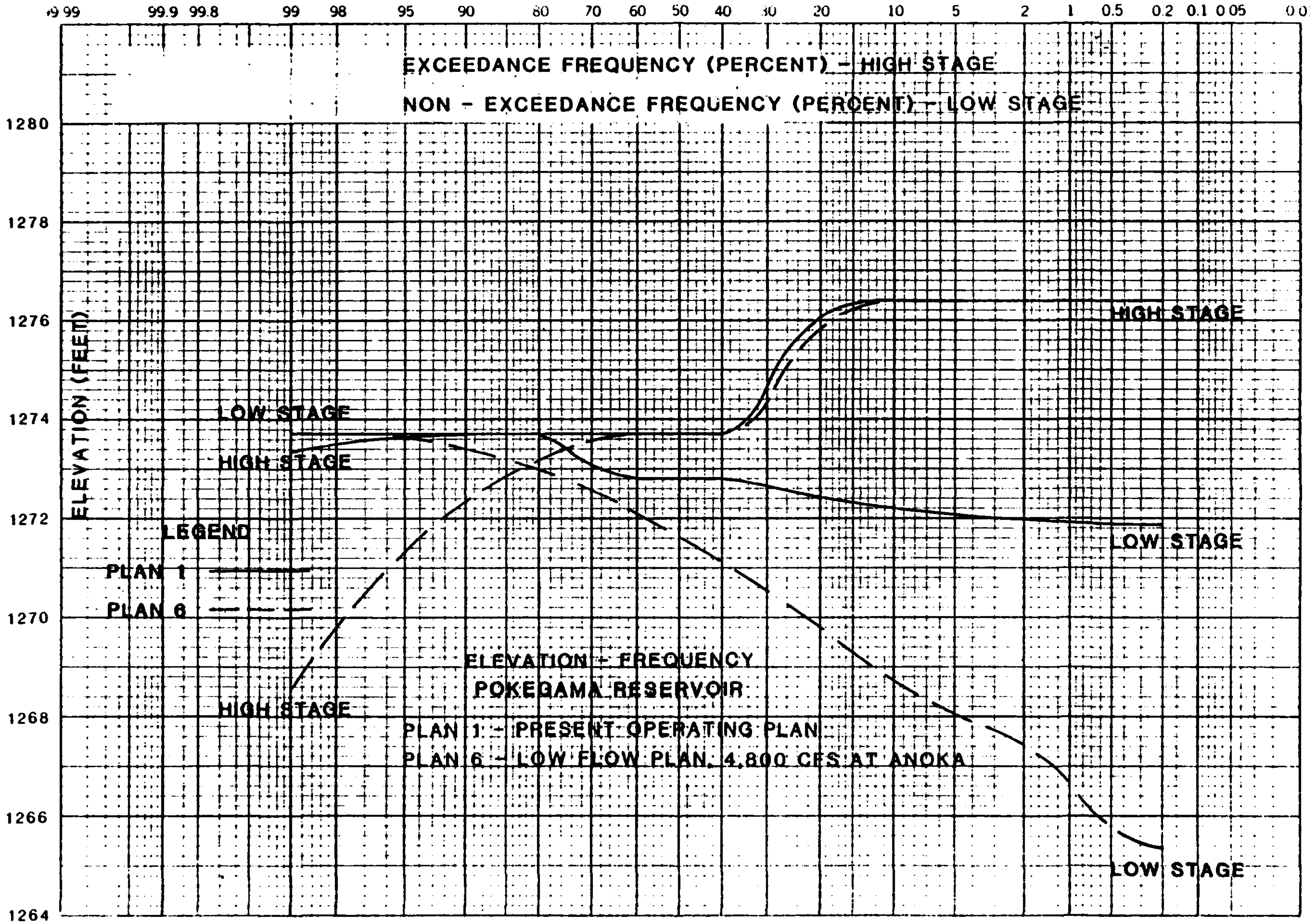
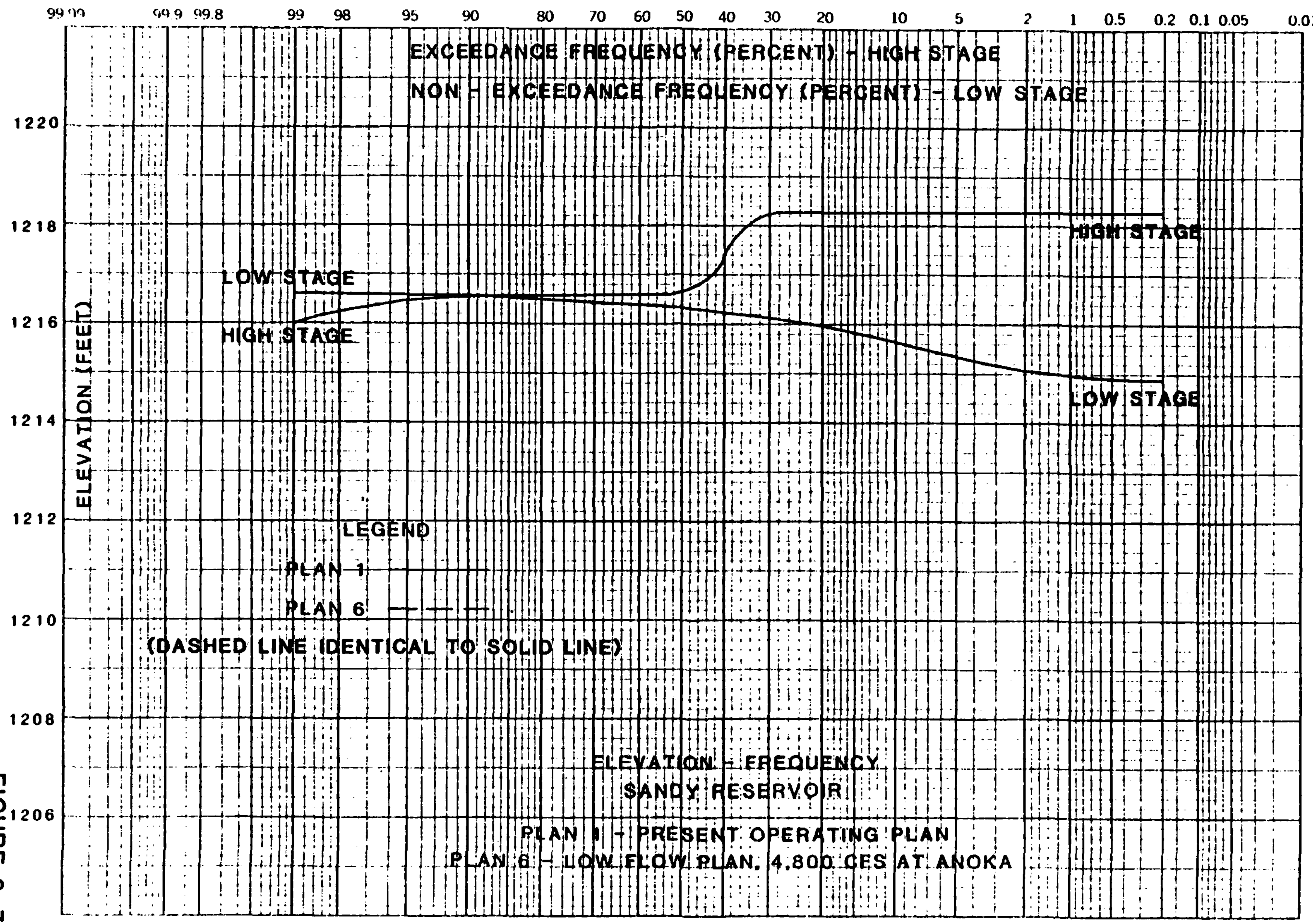

99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
1280
1278
1276
1274
1272
1270
1268
1266
1264
ELEVATION (FEET)
HIGH STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 6
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA

FIGURE 9-6



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
ELEVATION (FEET)
1220
1218
1216
1214
1212
1210
1208
1206
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 6
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA

FIGURE 9-7

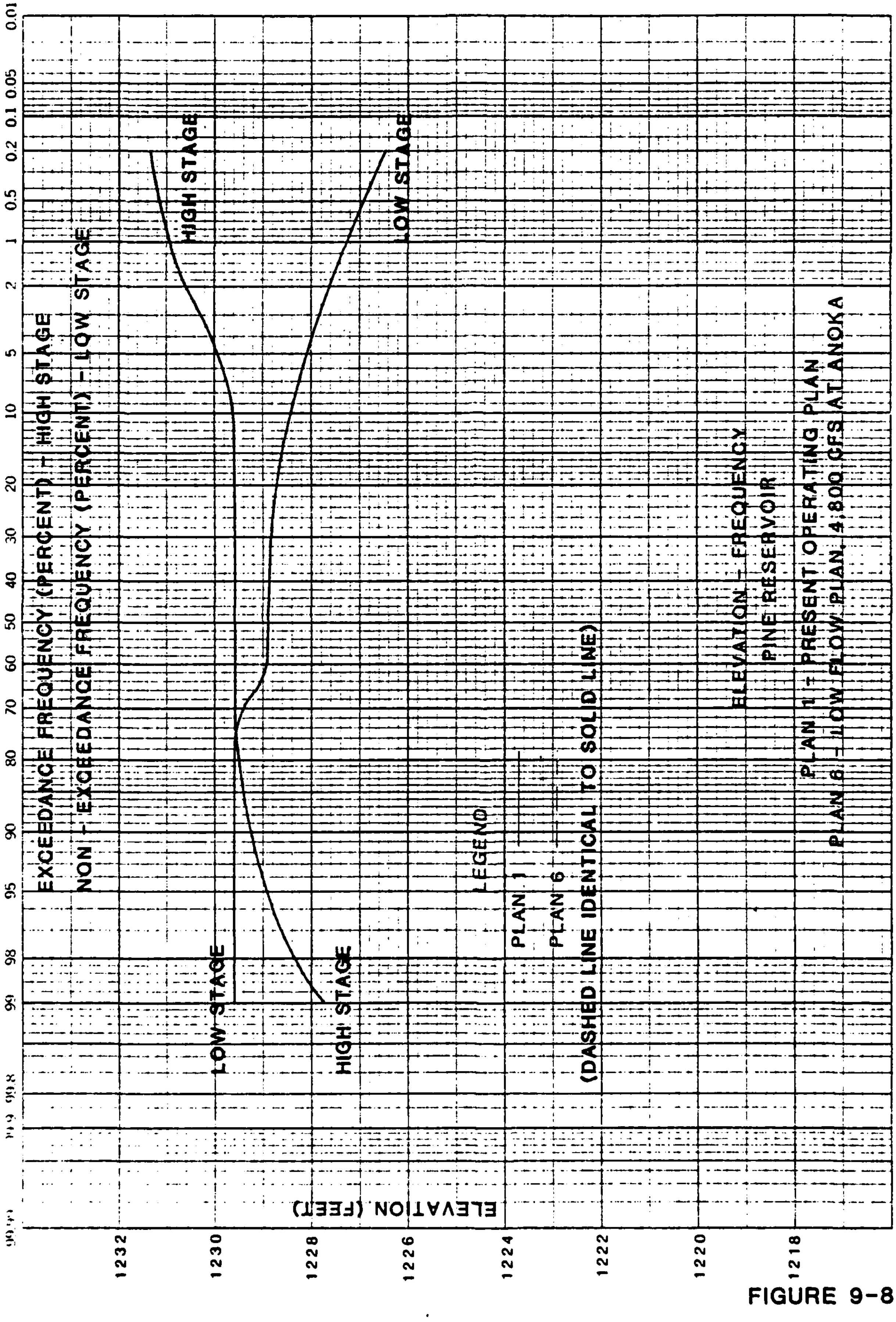
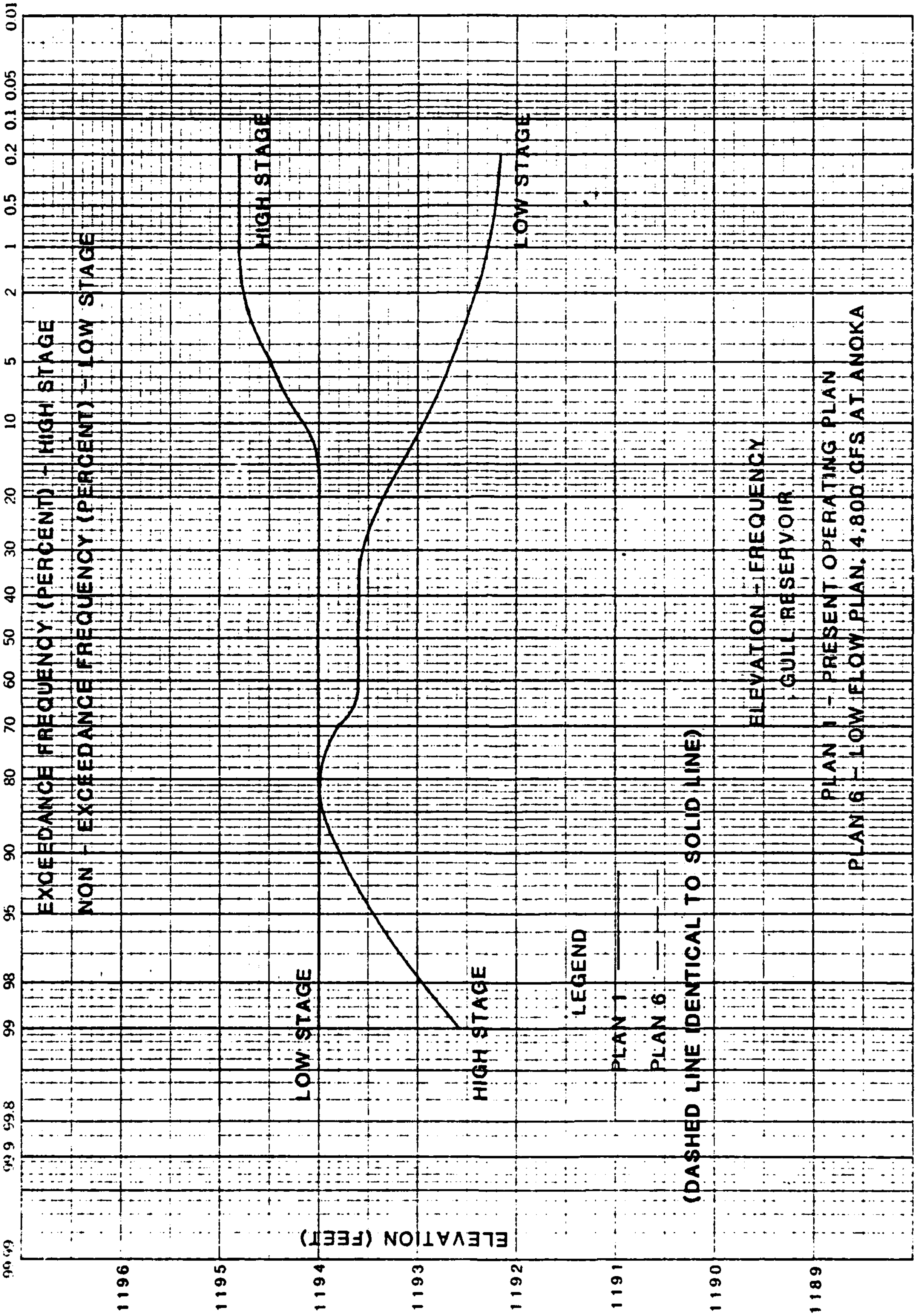

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 6
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA
ELEVATION (FEET)
1232
1230
1228
1226
1224
1222
1220
1218

FIGURE 9-8



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 6
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA
ELEVATION (FEET)
1196
1195
1194
1193
1192
1191
1190
1189

FIGURE 9-9

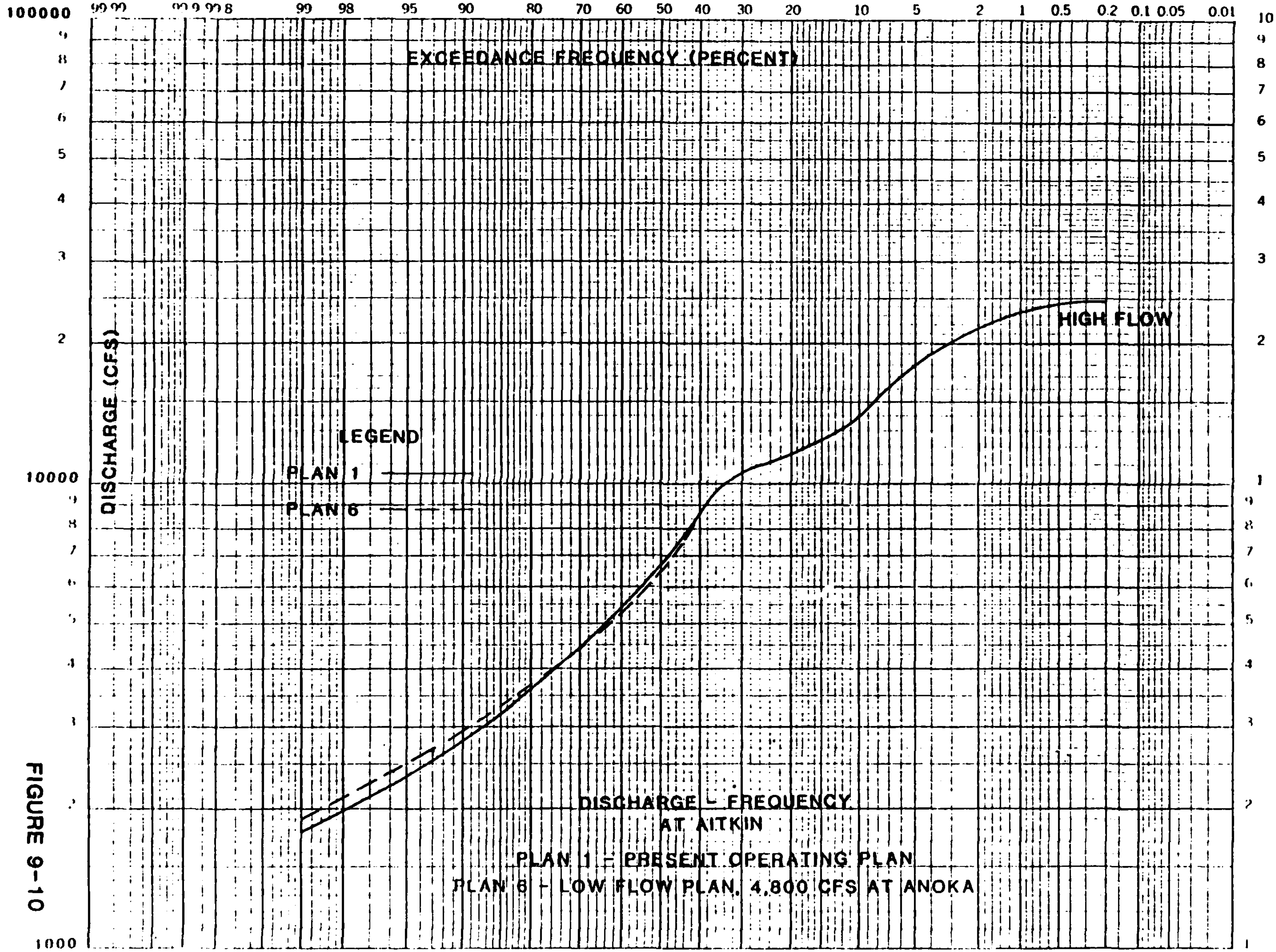

EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
99.99
99.9 99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1 0.05
0.01
100000
10000
1000
HIGH FLOW
LEGEND
PLAN 1
PLAN 6
DISCHARGE – FREQUENCY
AT AITKIN
PLAN 1 – PRESENT OPERATING PLAN
PLAN 6 – LOW FLOW PLAN, 4,800 CFS AT ANOKA

FIGURE 9-10

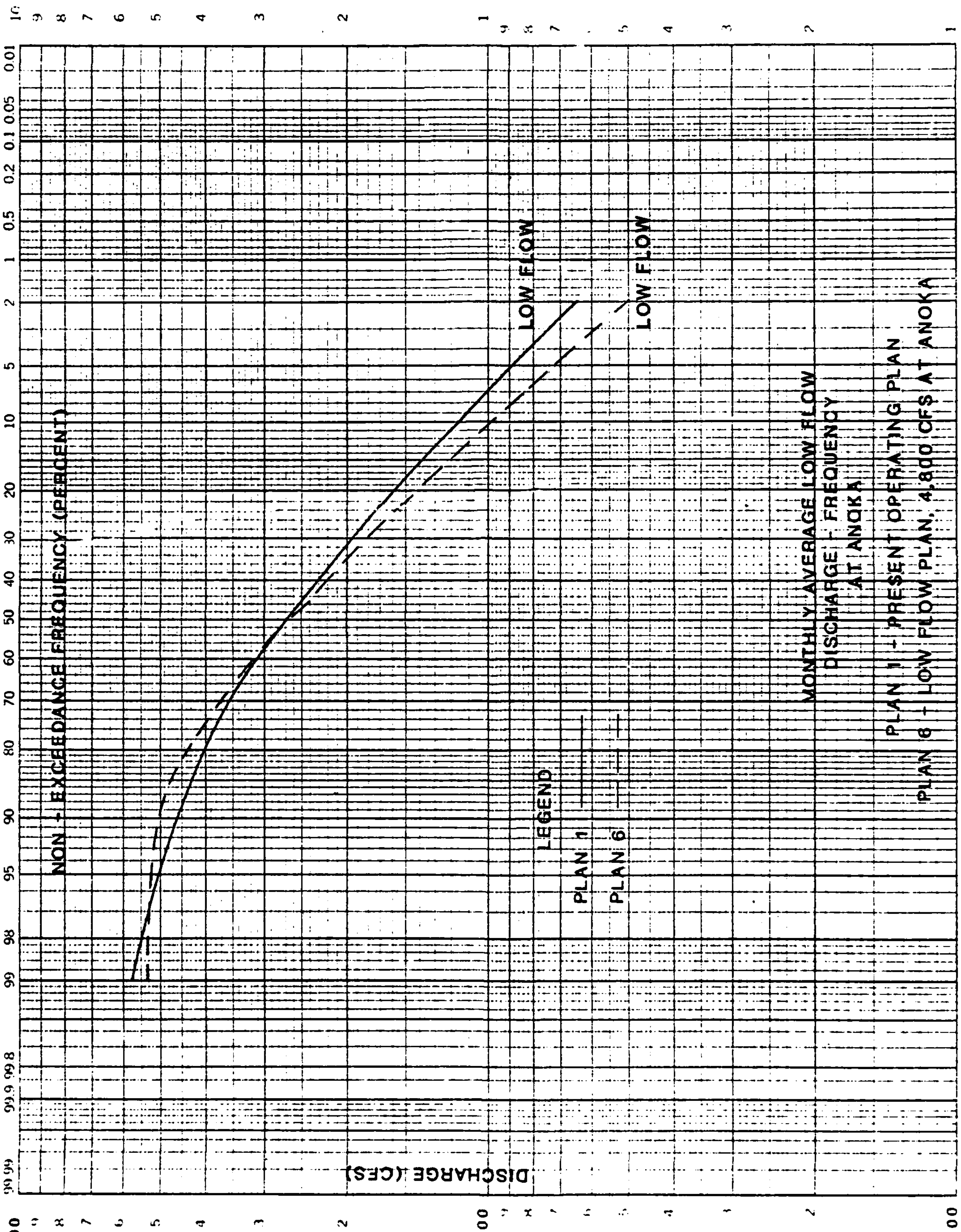

NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
LOW FLOW
LOW FLOW
LEGEND
PLAN 1
PLAN 6
MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 6 - LOW FLOW PLAN, 4,800 CFS AT ANOKA
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
10000
1000
100

FIGURE 9-11

SECTION 10

PLAN 7 - HYDROPOWER PLAN

OBJECTIVE

The objective for this Plan is to operate the reservoirs in a manner favorable to hydropower production requirements.

DISCUSSION

Specific analysis was not performed for this Plan. The results of Plan 6 - Low Flow Plan, 4,800 cfs at Anoka, provides an approximation of this requirement.

SECTION 11

PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN

OBJECTIVE

The primary objective of this plan is to minimize the sum of high and low stage damage at lake properties during the seasonal damage period (May - September).

DISCUSSION

This Plan puts the highest priority on reducing damages at the lakes. The current operating plan, Plan 1, does provide reservoir operation criteria which come close to this objective; however, Plan 1 also operates for Aitkin flood reduction requirements whereas this plan does not explicity operate for these requirements.

There are two main difficulties associated with achieving minimum lake property damage. The first involves the restricted downstream flow requirements and limited gate outlet capacities at the reservoirs. During summer periods of high reservoir inflow, the reservoir outlet capacities are not sufficient to prevent a water surface rise. In addition, during periods of extreme high flow when flooding is occurring at Aitkin, the reservoir flood control pool is used which contributes to lake property damage. The second difficulty relates to highly variable spring runoff (both timing and volume). As discussed previously, the reservoirs are operated to drawdown during early spring in anticipation of large reservoir inflows during the spring runoff period. Years with either extremely high or low spring runoff will cause the reservoirs to overshoot or undershoot the summer target levels, respectively.

For the purpose of this plan simulation, the summer target high and low level (index Levels 4 and 3, respectively) were both set at the minimum damage stage for each reservoir. The spring drawdown targets are the same as Plan 1, since this plan has been developed over the past years based upon experience gained from actual conditions. In addition, the reservoirs above Aitkin are not directly operated to reduce flood flow at Aitkin. Figures 11-1 through 11-6 provide the reservoir index level criteria.

RESULTS

The results of this plan show that the high stage for each reservoir exceeds reservoir Level 4 less often than for Plan 1. This attempted minimization of high reservoir stages often results in lower low stages in years with low spring runoff. In addition, the release of more water to keep the reser- voirs from filling above Level 4 results in higher high flows at Aitkin compared to Plan 1.

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin, and annual minimum flow at Anoka is provided in the tables in Appendix K together with plots of reservoir elevation versus time for the six reservoirs and streamflow at Aitkin and Anoka.

Frequency Results

Frequency relationships based on 47 years of simulated record are provided in Figures 11-7 through 11-14 for high and low stage at reservoirs, high flow at Aitkin, and low flow at Anoka.

Economic Results

Table 11-1 summarizes economic computations and compares this information to Plan 1, Present Operating Plan. The economic results show that high stage AAD is reduced at each reservoir when compared to Plan 1. This is expected based on Plan 8's operation policy of drawing down the reservoir level in early spring in anticipation of large inflows to the reservoirs during the spring runoff season. A side effect of this policy is that low stage damages increase because low spring runoff will not fill the reservoirs up to the summer target levels. However, overall the total AAD of the six reservoirs is decreased from $320.9K (Plan 1) to $222.6K (Plan 8). The largest percent decrease occurs at Pokegama Reservoir (82 percent decrease), as this reservoir no longer has to try to minimize high flows at Aitkin. The savings in reduced lake property damage ($98.3K per year), however, is more than offset by increased high flow damage at Aitkin. Aitkin AAD rises from $278.6K (Plan 1) to $417.6K (Plan 8), an increase of $139K. This results in an overall increase in AAD of $40.7K for Plan 8 when compared to Plan 1.

The average annual cost (AAC) of not supplying a minimum of 1600 cfs at Anoka was also calculated for Plan 8, although it was not the explicit purpose of Plan 8 to meet this requirement. However, by calculating the AAC it was then possible to compare Plan 8's average annual net benefit (or cost) relative to Plan 1. The AAC for Plan 8 is $3237.3K compared to $3189.9K for Plan 1. The relative net cost of Plan 8 at Anoka is $47.4K.

TABLE 11-1

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 8	PLAN 1
Winnibigoshish		
High Stage	2.9	4.0
Low Stage	8.0	9.7
Total	10.9	13.7
Leech		
High Stage	1.7	11.0
Low Stage	75.1	71.3
Total	76.8	82.3
Pokegama		
High Stage	0.6	25.0
Low Stage	4.5	2.8
Total	5.1	27.8
Sandy		
High Stage	22.5	29.4
Low Stage	4.7	2.1
Total	27.2	31.5
Pine		
High Stage	5.8	16.6
Low Stage	9.5	6.3
Total	15.3	22.9
Gull		
High Stage	66.3	127.5
Low Stage	21.0	15.2
Total	87.3	142.7
Aitkin		
High Flow	417.6	278.6
TOTAL AAD	640.2	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	3,237.3	3,189.9

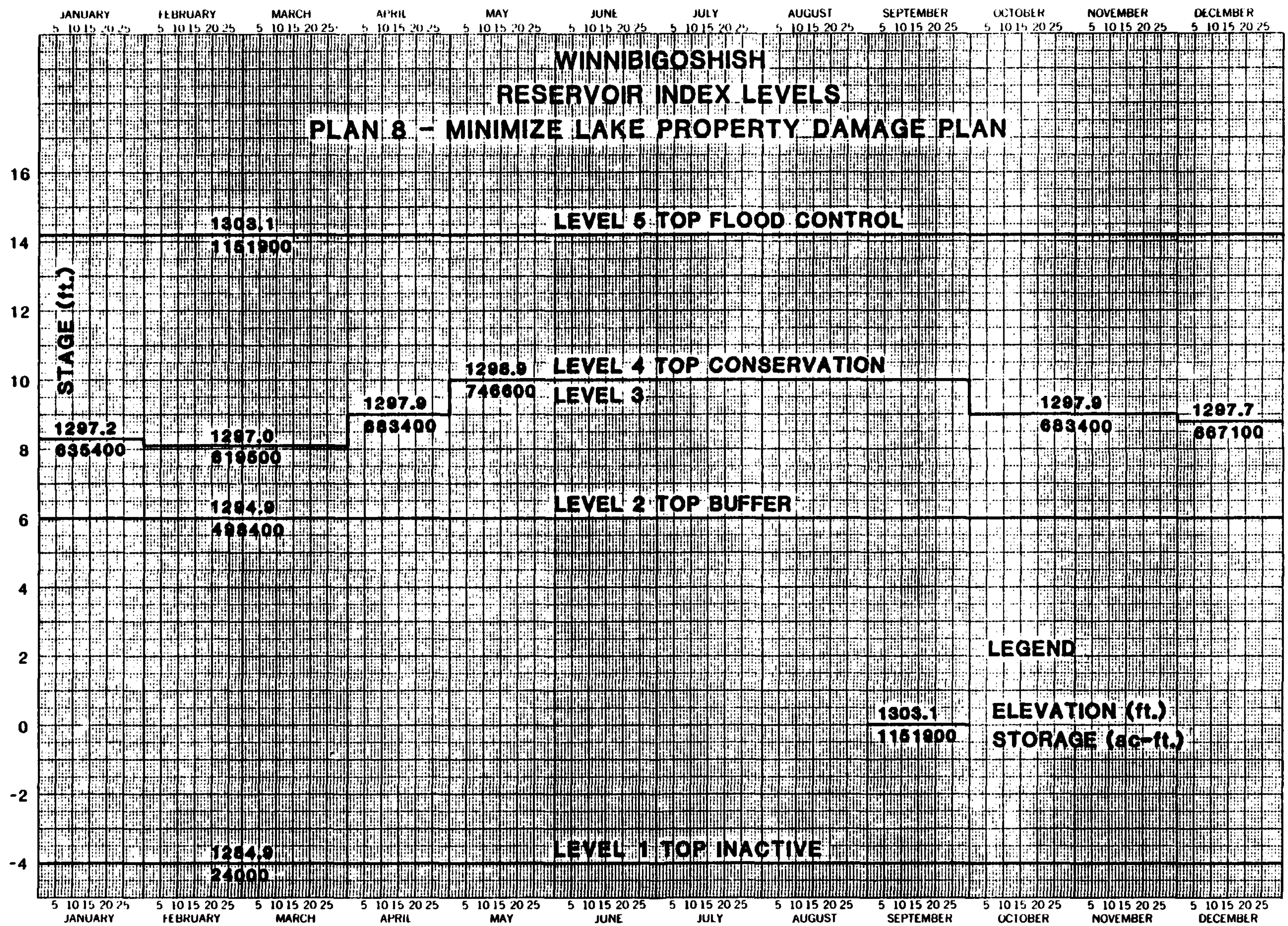
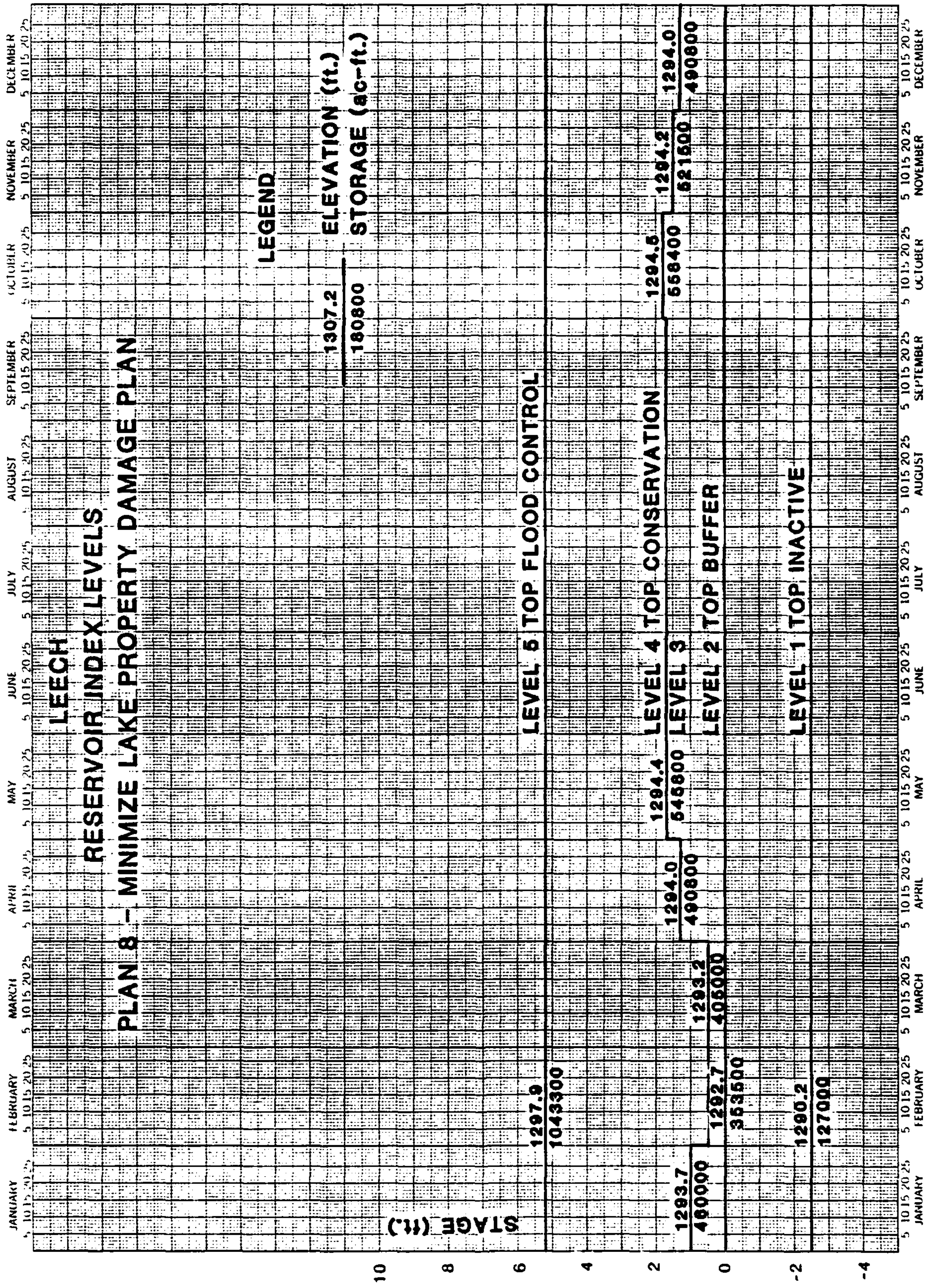

WINNIBIGOSHISH
RESERVOIR INDEX LEVELS
PLAN 8 – MINIMIZE LAKE PROPERTY DAMAGE PLAN
STAGE (ft.)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1303.1
1151900
1297.2
635400
1297.0
619500
1297.9
683400
1298.9
746600
1297.9
683400
1297.7
667100
1294.9
498400
1264.9
24000
LEGEND
1303.1
1151900
ELEVATION (ft.)
STORAGE (ac-ft.)
JANUARY FEBRUARY MARCH APRIL MAY JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER
5 10 15 20 25
16 14 12 10 8 6 4 2 0 -2 -4

FIGURE 11-1



LEECH
RESERVOIR INDEX LEVELS
PLAN 8 – MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEGEND
1307.2
180800
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1297.9
1043300
1293.7
460000
1292.7
353500
1293.2
405000
1290.2
127000
1294.0
490800
1294.4
545800
1294.5
558400
1294.2
521500
1294.0
490800
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 11-2

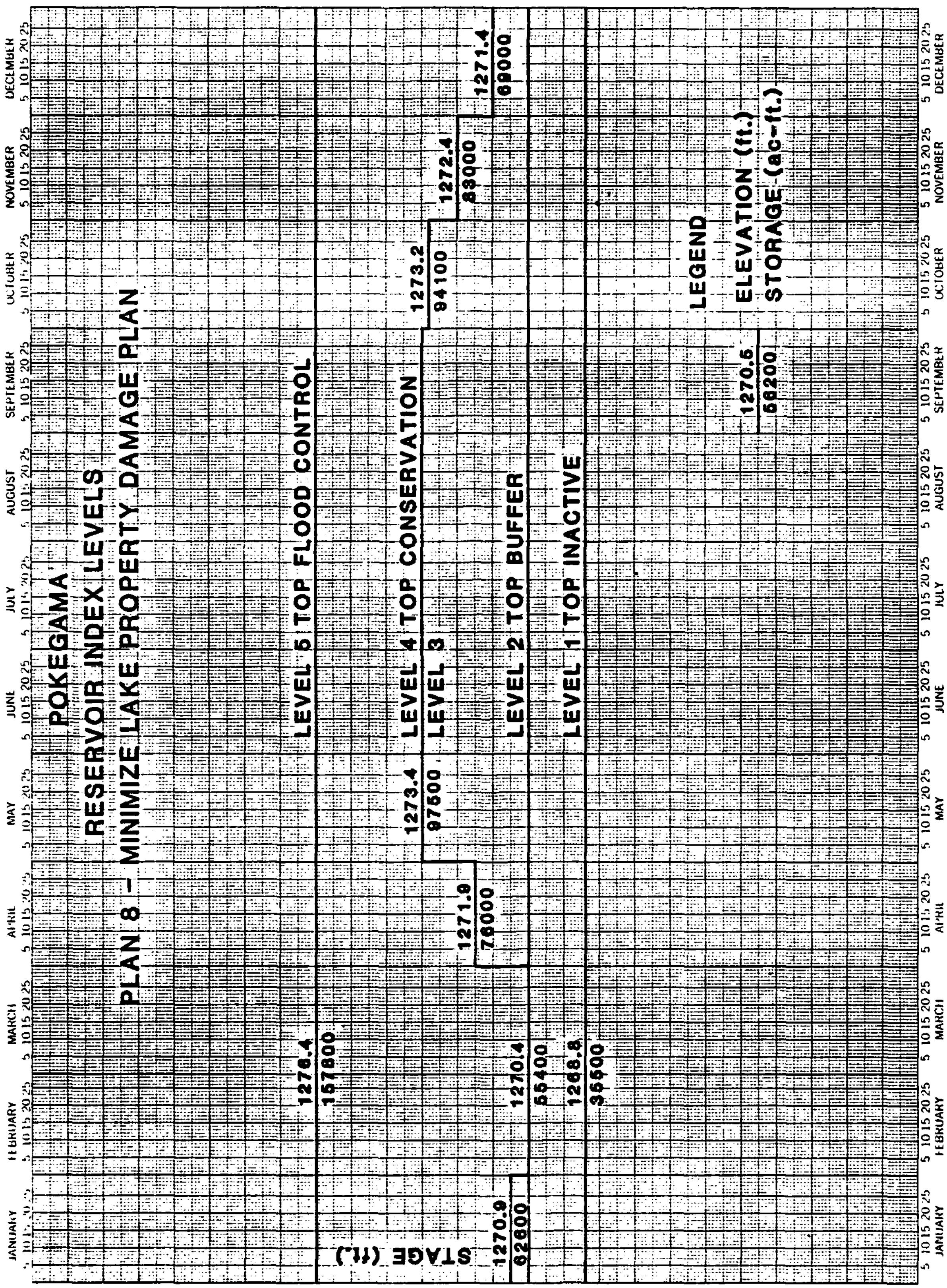
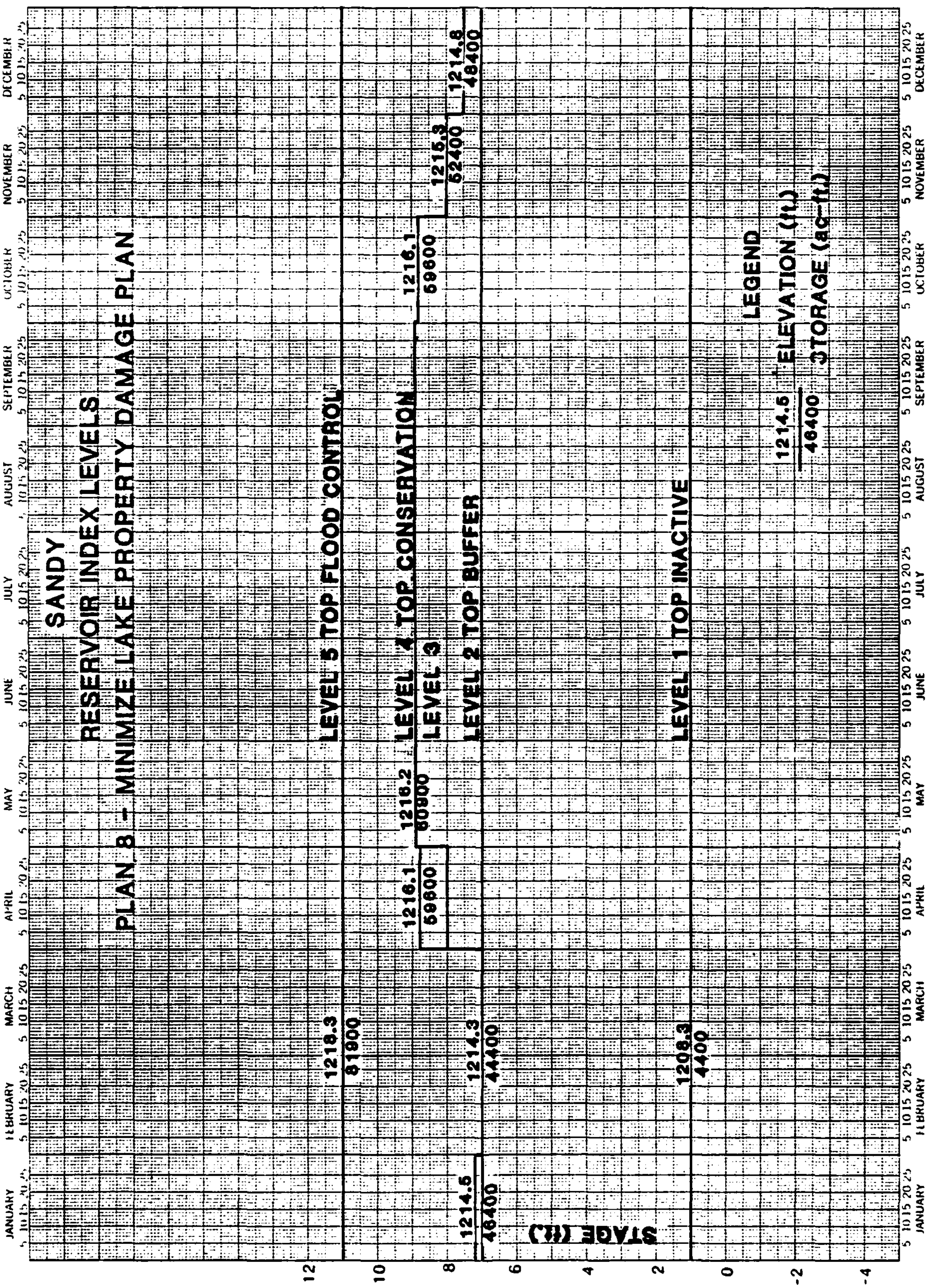

POKEGAMA
RESERVOIR INDEX LEVELS
PLAN 8 – MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
1276.4
157800
1270.9
62600
1270.4
55400
1268.8
36600
1271.9
76000
1273.4
97500
1273.2
94100
1272.4
83000
1271.4
69000
1270.6
58200
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
12
10
8
6
4
2
0
-2
-4

FIGURE 11-3



SANDY
RESERVOIR INDEX LEVELS
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1218.3
81900
1214.5
46400
1214.3
44400
1208.3
4400
1216.1
59600
1216.2
60900
1216.1
59600
1215.3
52400
1214.8
48400
LEGEND
1214.5 ELEVATION (ft.)
46400 STORAGE (ac-ft.)
STAGE (ft.)
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 11-4

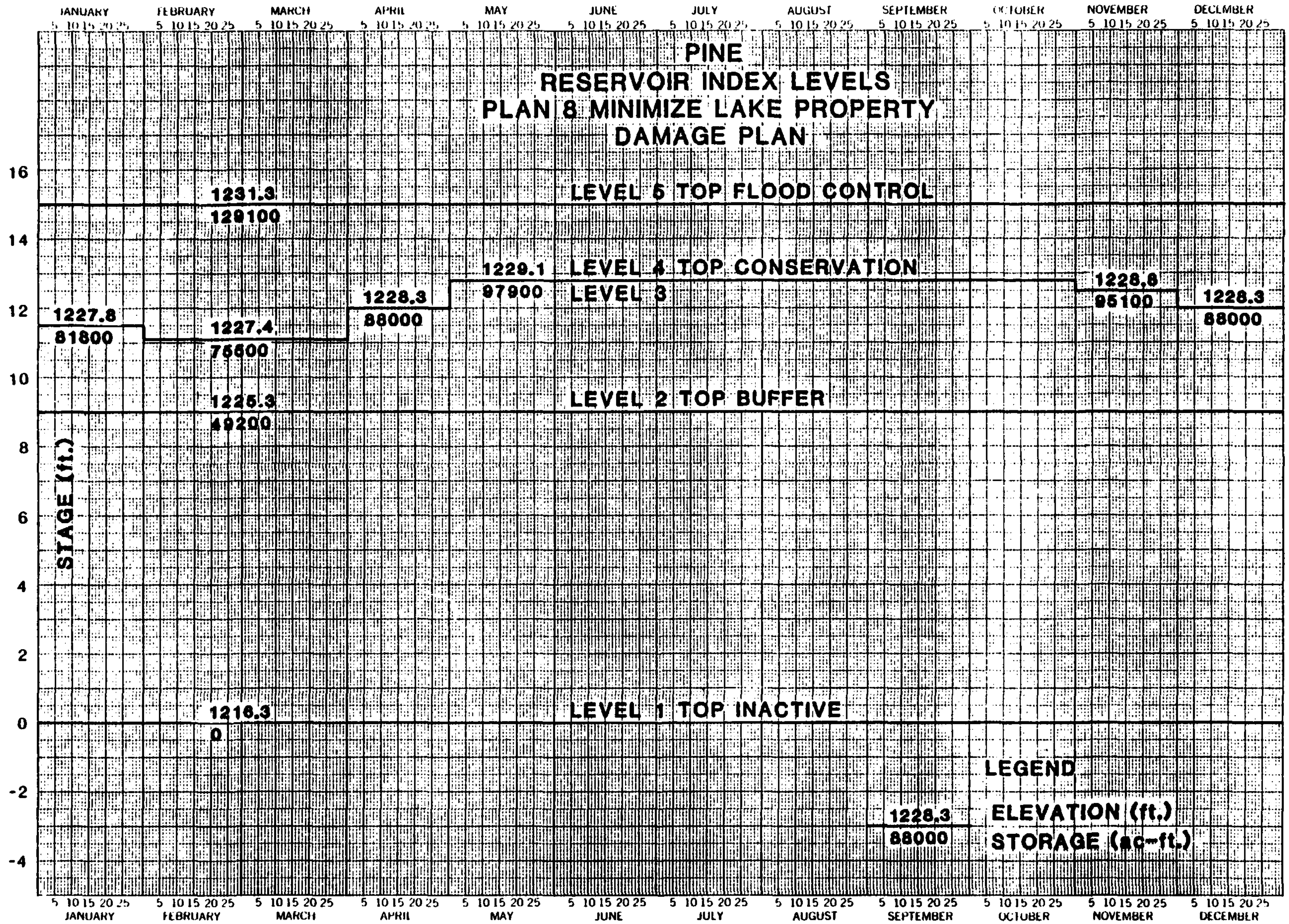

PINE
RESERVOIR INDEX LEVELS
PLAN 8 MINIMIZE LAKE PROPERTY
DAMAGE PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
1231.3
129100
1227.8
81800
1227.4
75600
1228.3
88000
1229.1
97900
1228.8
95100
1228.3
88000
1225.3
49200
1216.3
0
LEGEND
1228.3
88000
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25

FIGURE 11-5

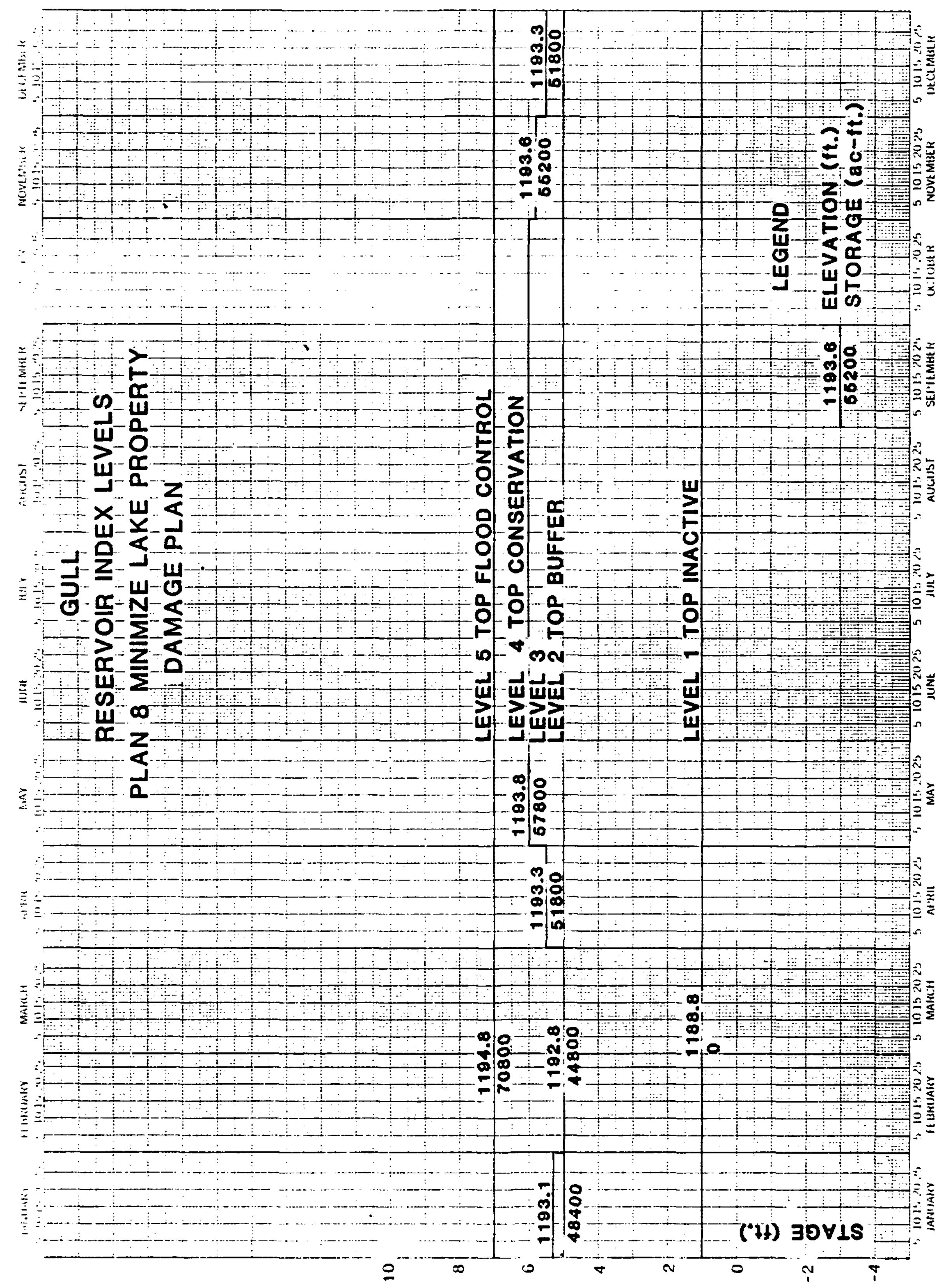

GULL
RESERVOIR INDEX LEVELS
PLAN 8 MINIMIZE LAKE PROPERTY
DAMAGE PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
STAGE (ft.)
1193.1
48400
1194.8
70800
1192.8
44800
1188.8
0
1193.3
51800
1193.8
57800
1193.6
55200
1193.6
55200
1193.3
51800
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
10
8
6
4
2
0
-2
-4

FIGURE 11-6

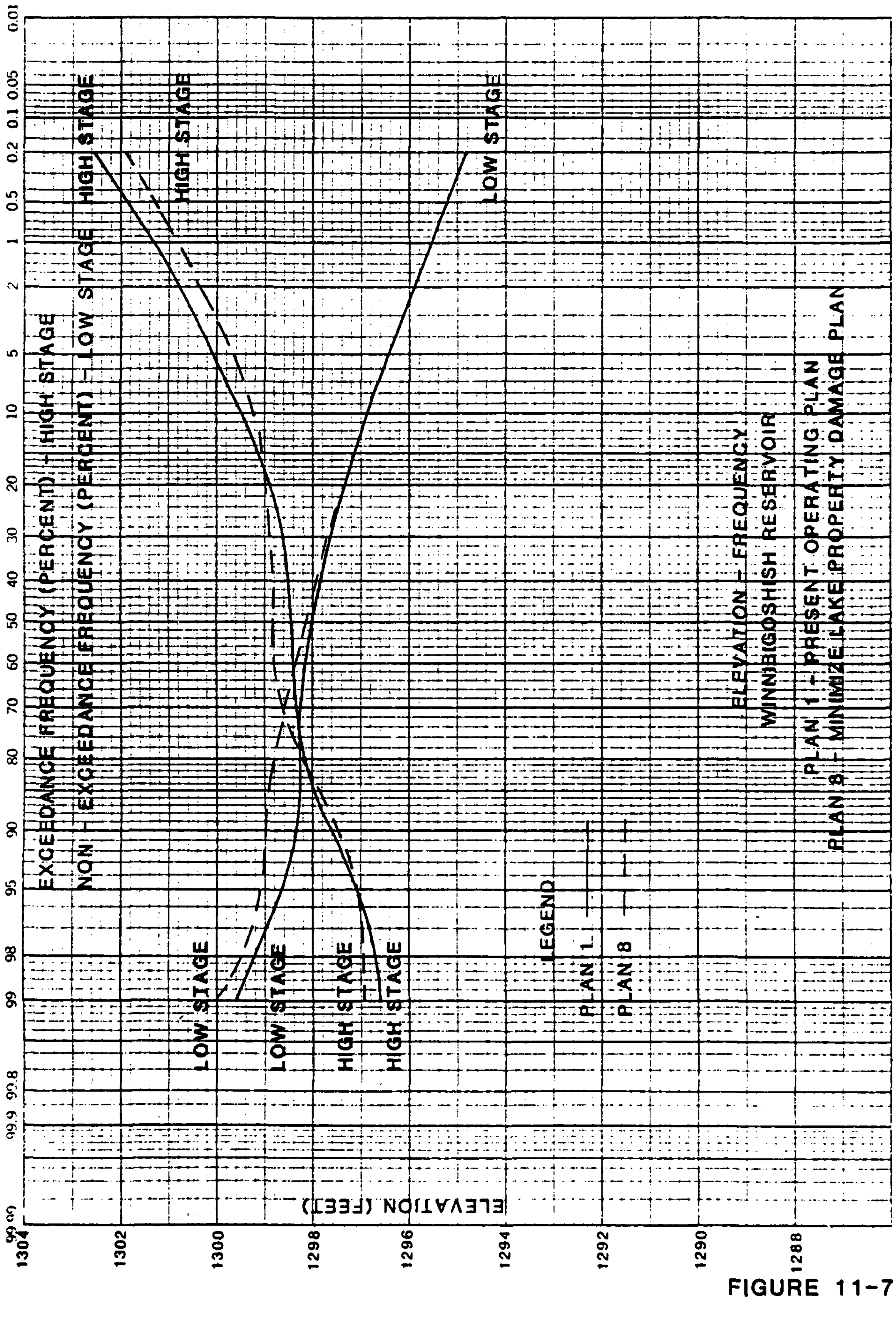
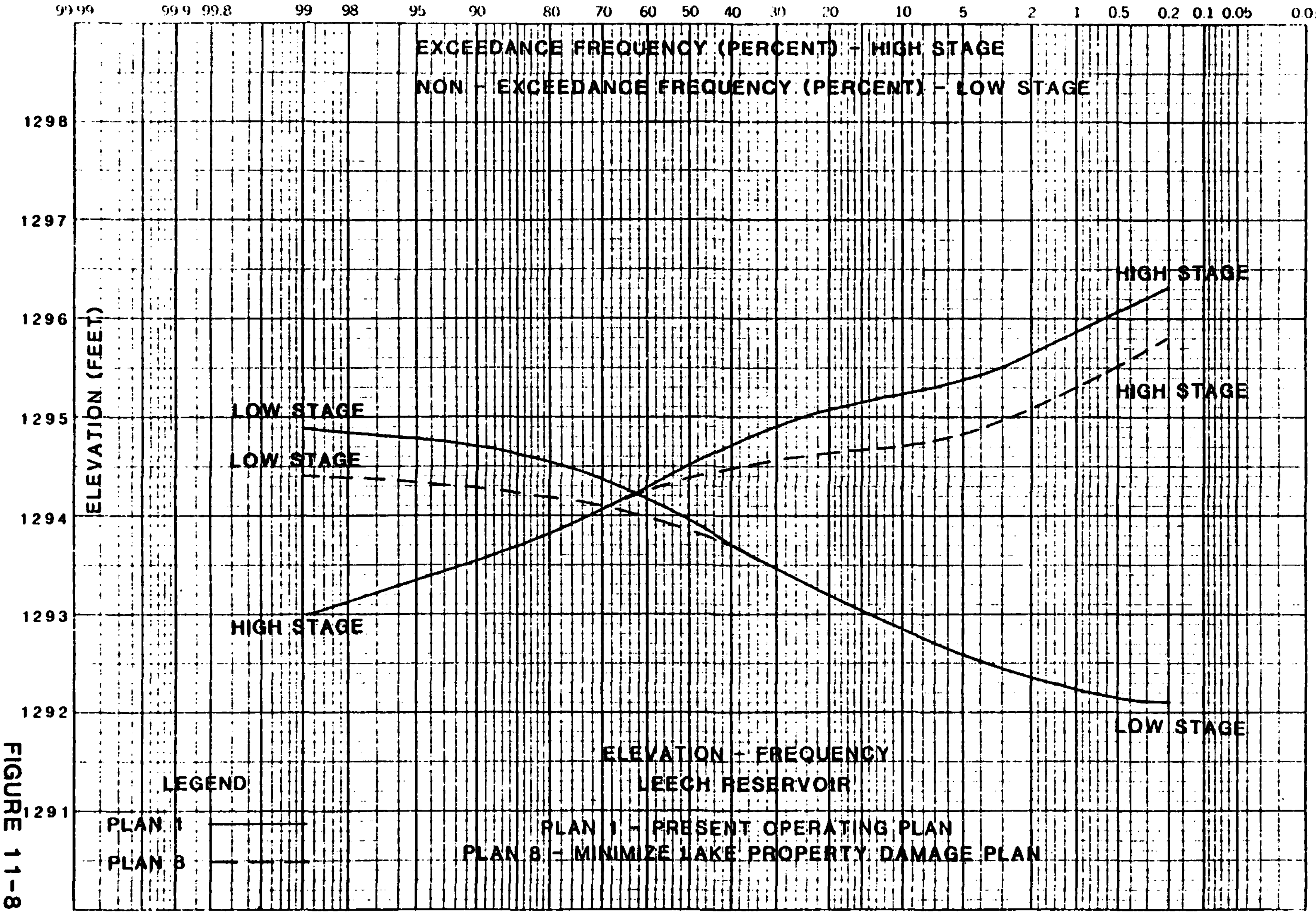
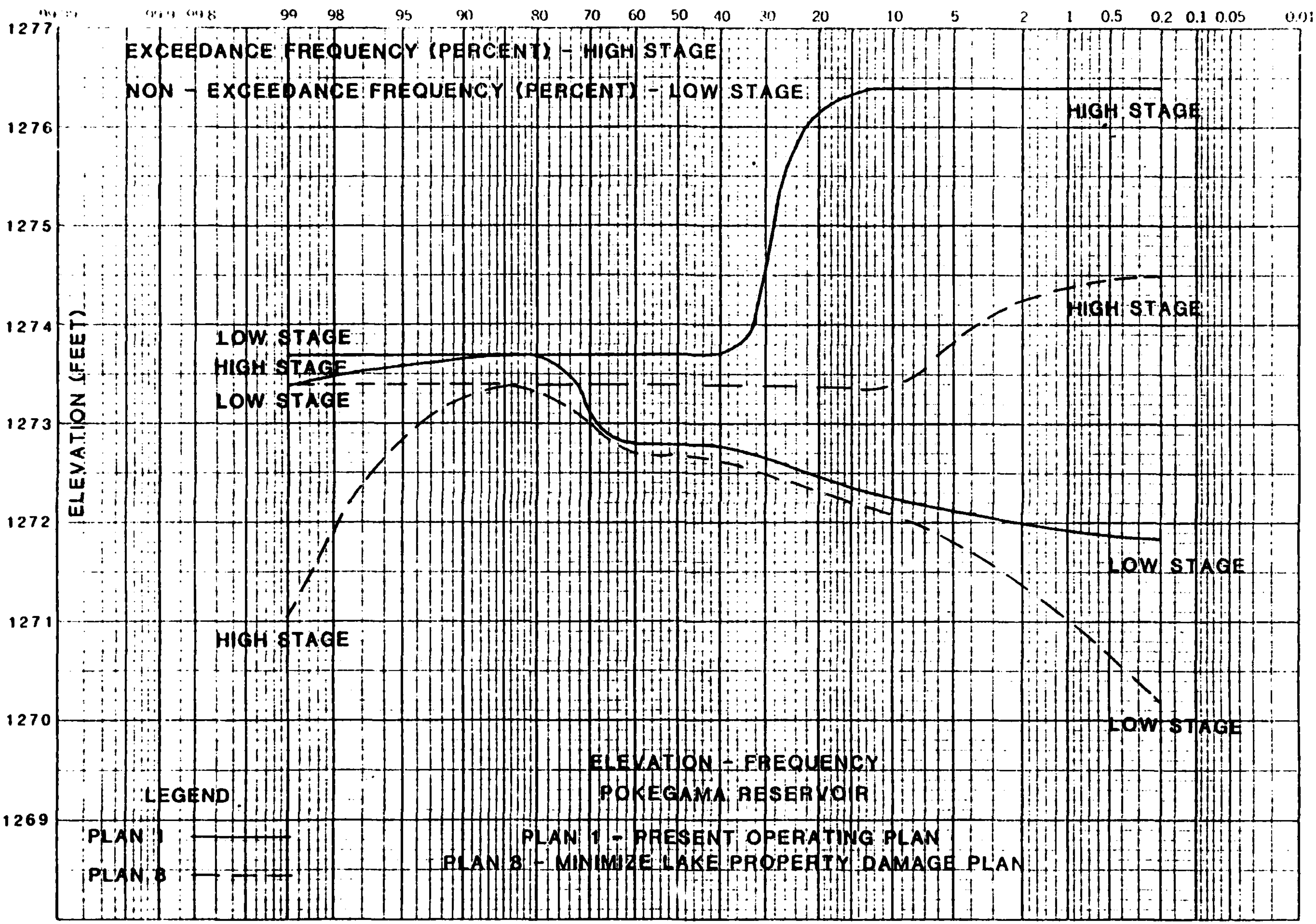

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEGEND
PLAN 1
PLAN 8
ELEVATION (FEET)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1304
1302
1300
1298
1296
1294
1292
1290
1288

FIGURE 11-7



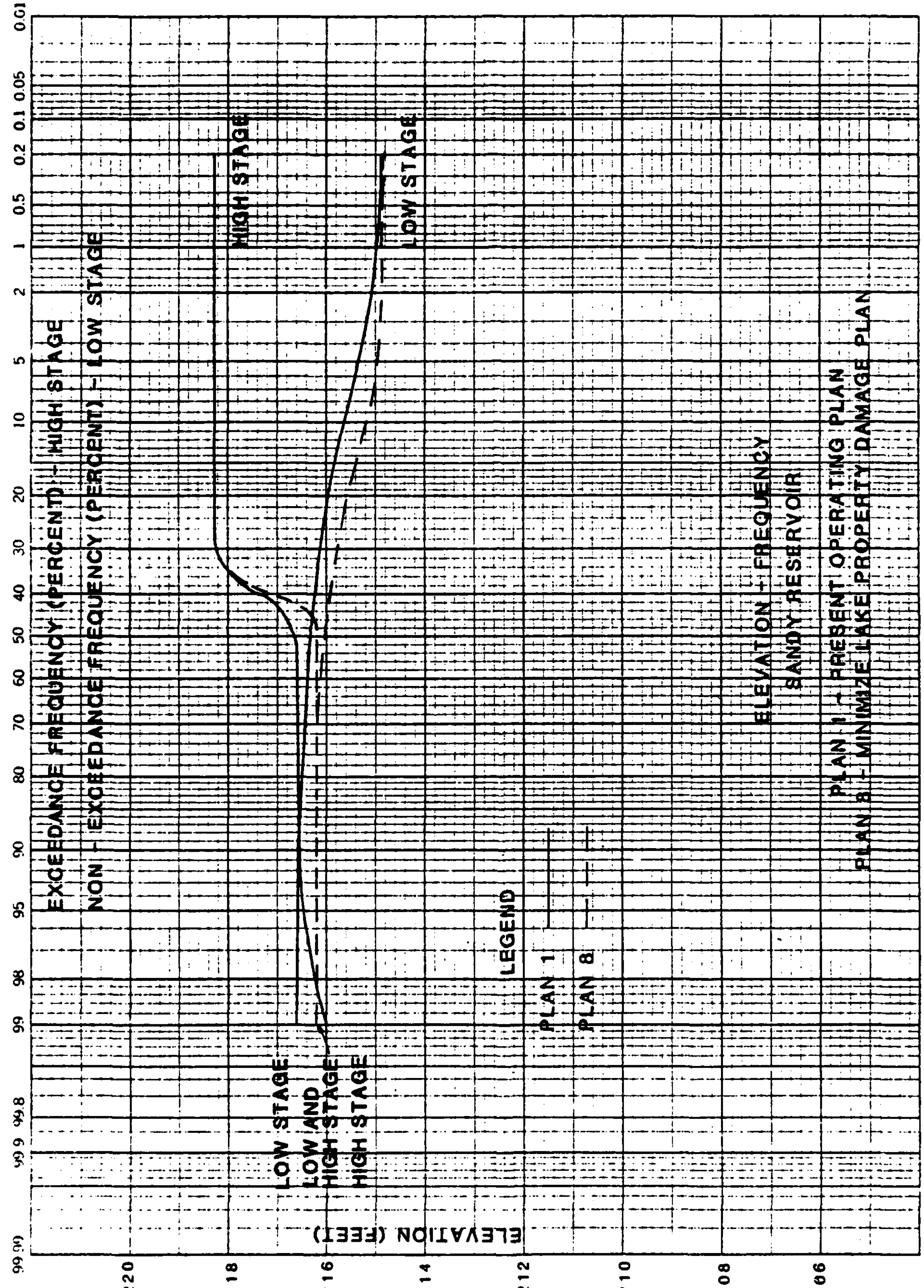
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
ELEVATION (FEET)
1298
1297
1296
1295
1294
1293
1292
1291
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEGEND
PLAN 1
PLAN 8

FIGURE 11-8



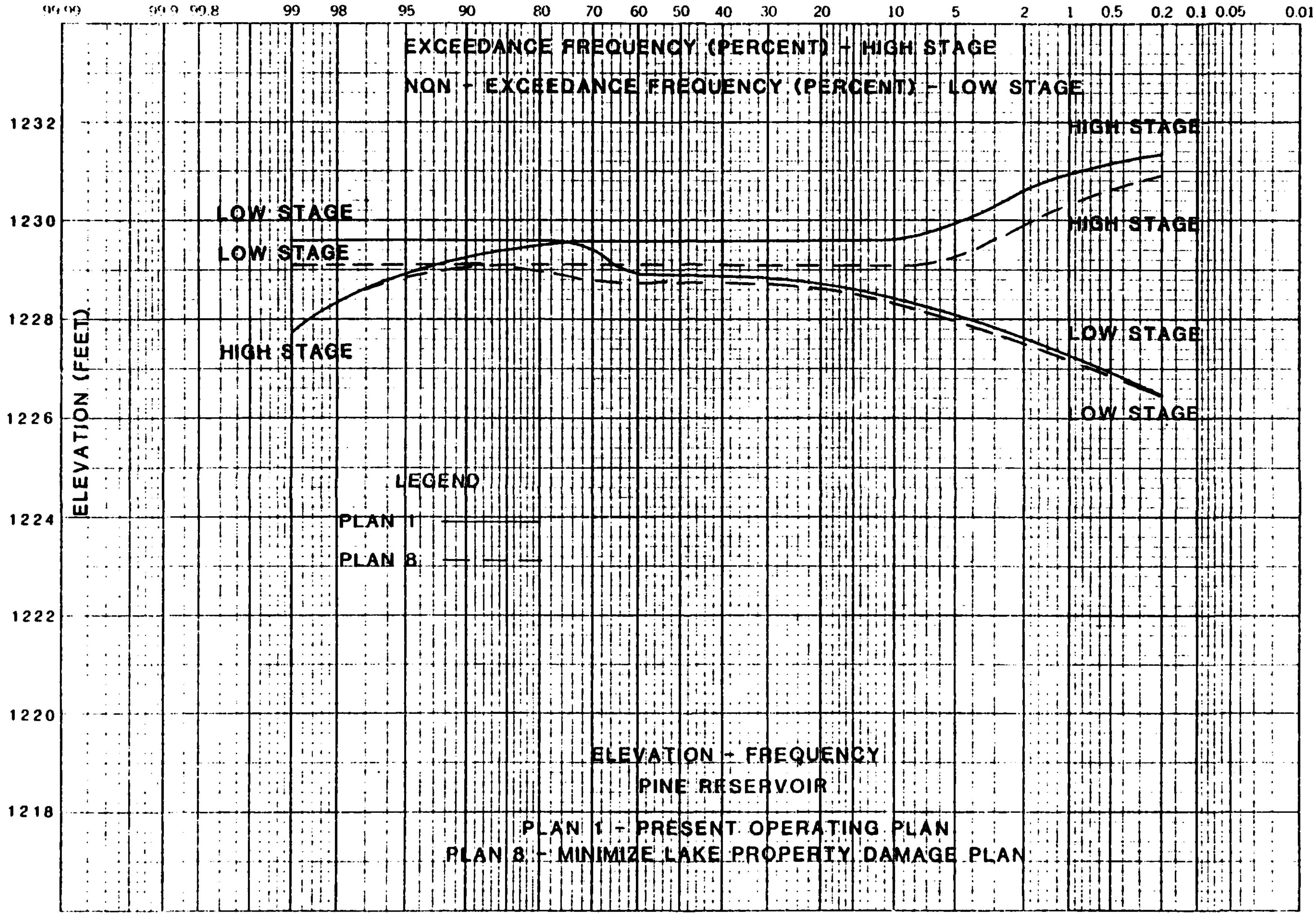
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
1277 1276 1275 1274 1273 1272 1271 1270 1269
HIGH STAGE
HIGH STAGE
LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
LEGEND
PLAN 1
PLAN 8
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN

FIGURE 11-9



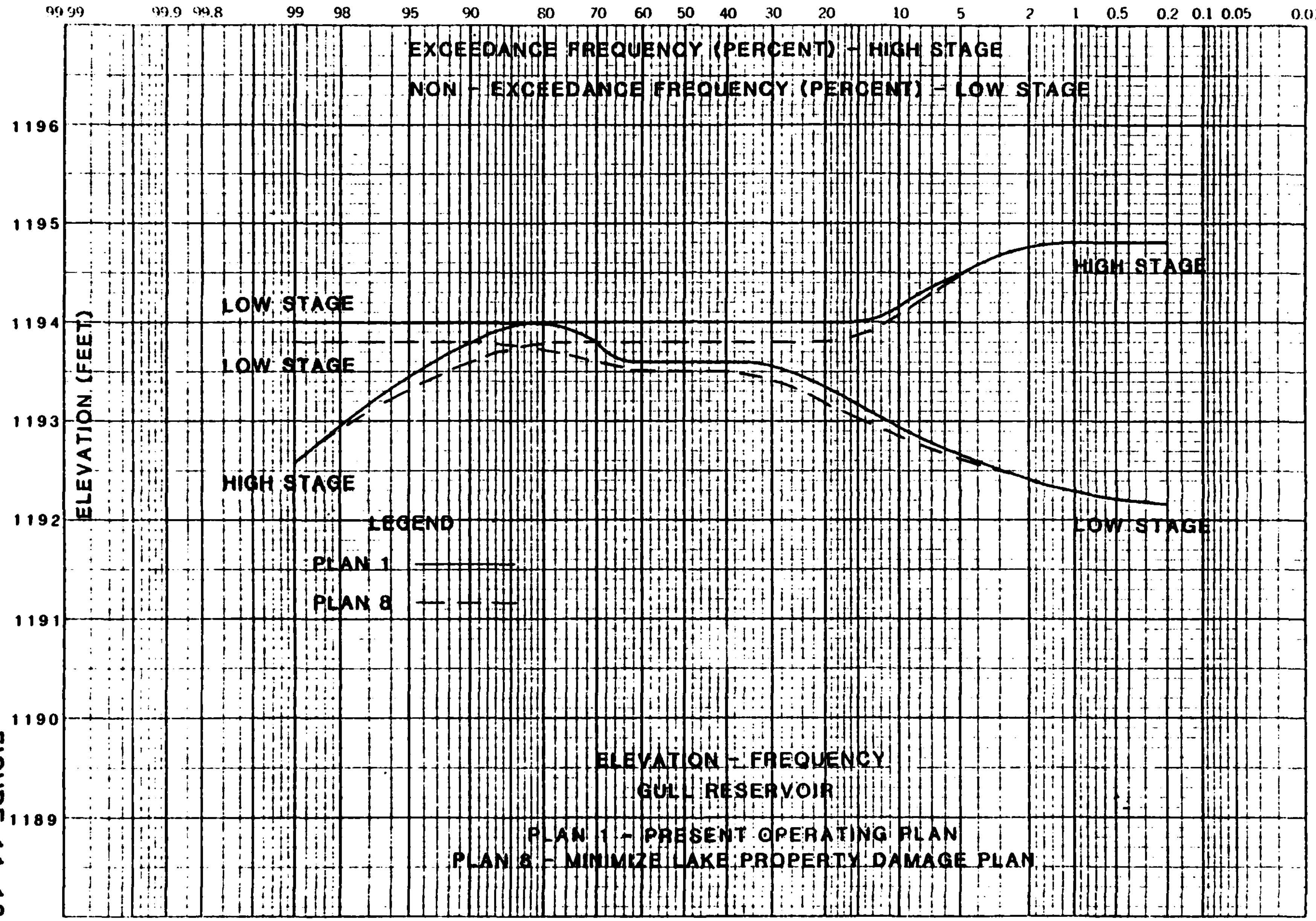
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN
LEGEND
PLAN 1
PLAN 8
HIGH STAGE
LOW STAGE
LOW STAGE
LOW AND HIGH STAGE
HIGH STAGE
ELEVATION (FEET)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1220
1218
1216
1214
1212
1210
1208
1206

FIGURE 11-10



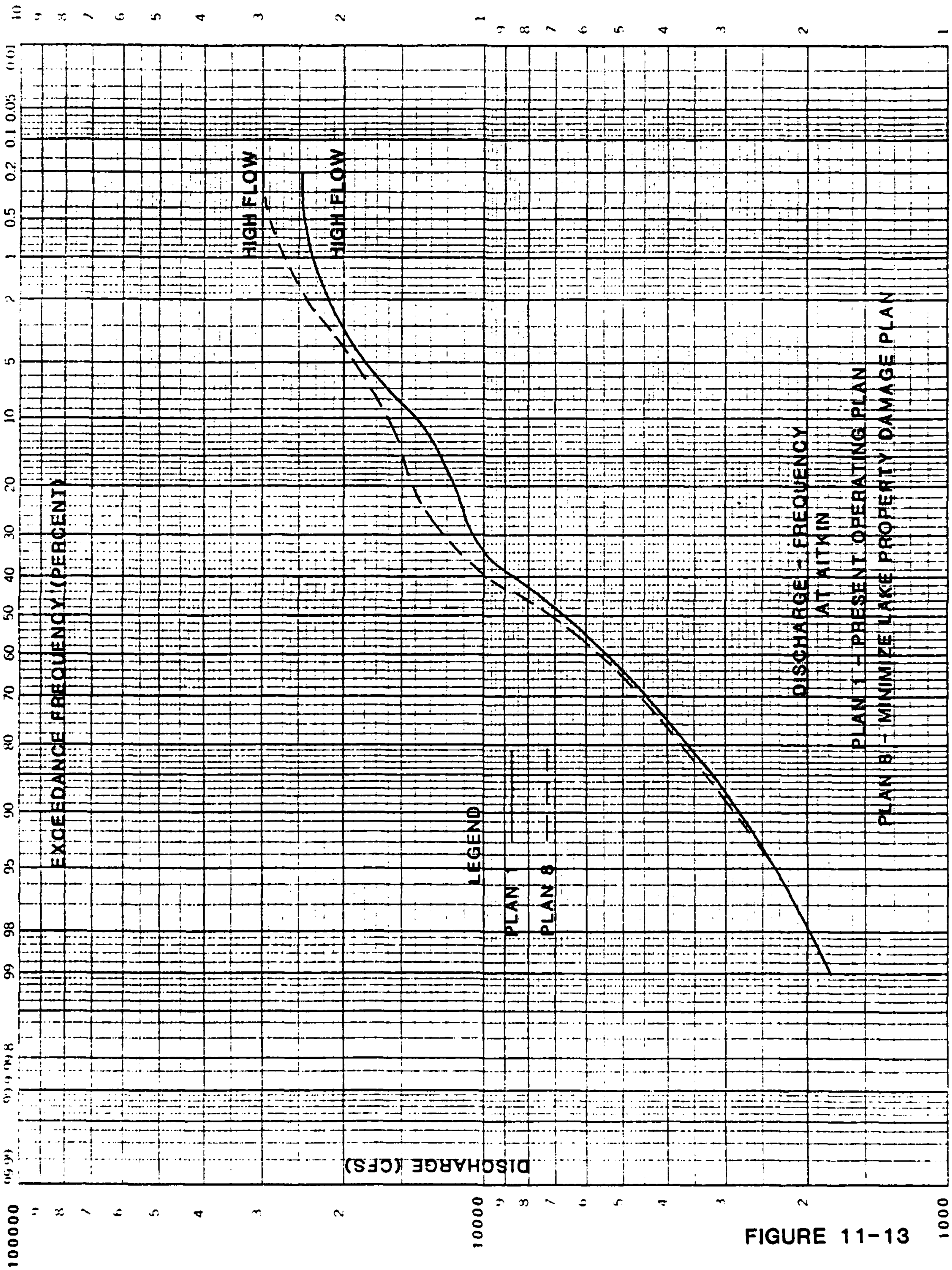
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1232
1230
1228
1226
1224
1222
1220
1218
ELEVATION (FEET)
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 8
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN

FIGURE 11-11



EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
ELEVATION (FEET)
1196
1195
1194
1193
1192
1191
1190
1189
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LOW STAGE
LEGEND
PLAN 1
PLAN 8
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN

FIGURE 11-12



DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN
EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
HIGH FLOW
LEGEND
PLAN 1
PLAN 8
100000
10000
1000

FIGURE 11-13

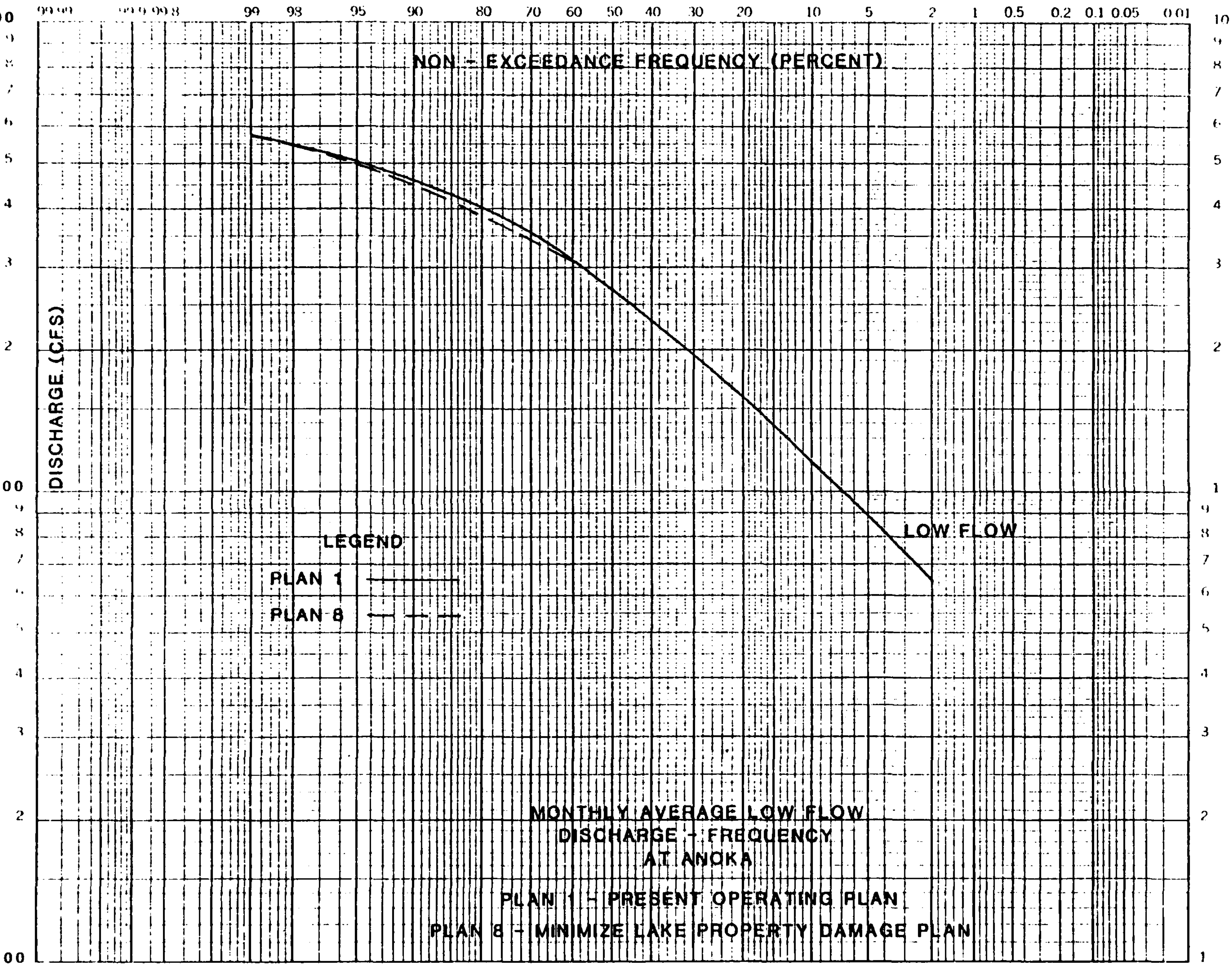

NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (C.F.S)
LOW FLOW
LEGEND
PLAN 1
PLAN 8
MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 8 - MINIMIZE LAKE PROPERTY DAMAGE PLAN

FIGURE 11-14

SECTION 12

PLAN 9 - CONSERVATION PLAN

OBJECTIVE

The plan has two objectives, Leech Reservoir operation for the purpose of improving wild rice growing conditions and Winnibigoshish Reservoir operation for the purpose of improving walleye spawning.

DISCUSSION

The Leech Lake criteria for optimum wild rice production are shown on Figure 12-1. Lake Winnibigoshish criteria for improving walleye spawning are contained in the following quote by Colonel William W. Badger, District Engineer for St. Paul District, in his letter dated 23 February 1981 to Mr. Joseph Alexander, Commissioner Minnesota Department of Natural Resources:

> As in the case of our agreement with the State of Minnesota for the trial period of 1975-1980 to regulate Winnibigoshish at a 9.0 to 9.5 summer stage, I feel it is possible to continue to regulate the reservoir towards this goal and accommodate a modification in regulation to meet the desires of the Fisheries Division. In summary, the District will follow the past practice of regulation to meet the drawdown stage of 8.0 feet by 1 April and summer stages of 9.0 - 9.5 feet. We will coordinate with the Fisheries Division through the winter and into the spawning season to meet the goals of 8.5 feet stage at the beginning of spawning season (around 25 April) and a slow lake rise during spawning season (about 2-3 weeks). We will endeavor to maintain this method of regulation on a trial basis beginning in September 1981 and continuing through September 1986.

Leech Lake

The reservoir operating criteria require a period of uniform lake level rise (1 April to 15 May). This is followed by criteria specifying a constant lake level with permissible maximum fluctuations in a 48-hour period (16 May - 10 September). Due to the downstream flow restrictions and limited gate discharge capacities, there are periods when reservoir inflow is too large for the physical outlet capacity of the reservoir to keep the water surface within the specified limits. Using the reservoir

parameters specified in Table 12-1, the reservoir inflow limits are shown on Figures 12-2, 12-3, and 12-4 with plots of reservoir inflow for representative periods where the maximum limits are exceeded, no limits are exceeded and the minimum limit is exceeded, respectively. If actual inflow is outside of these limits, the Leech Lake Conservation Plan criteria will be violated.

TABLE 12-1

LEECH LAKE PARAMETERS AFFECTING CONSERVATION PLAN

	April 1	May 15 - Sept. 10
Elevation (ft)	1,293.7	1,294.4
Storage (ac-ft)	461,510	545,770
Outlet Capacity (cfs)	960	1,810
Daily Net Inflow for 1 inch Elevation Rise (SFD)	4,580	5,300

Due to the 48-hour criteria, daily flow simulation throughout the period of record (1930-1976) is desirable. Since this flow data is not available, an approximate analysis is performed using the combined monthly and daily flow series which is used for evaluating all plans in this study. Figure 12-6 provides the Leech Reservoir index levels for this plan. The effect of setting index levels 2, 3, and 4 equal during the summer months (as shown in Figure 12-6) is to minimize changes in the reservoir water surface elevation during the wild rice growing season (May to September).

Winnibigoshish Lake

The Lake Winnibigoshish criteria for improving walleye spawning are very similar to the Present Operating Plan, Plan 1. As for the Leech Lake analysis, it would be desirable to simulate the active period of record with daily flows to fully evaluate the potential fluctuations during the critical period (1 April through 1 June). Simulation is performed with the combined monthly and daily flow series using the Winnibigoshish Reservoir index level criteria shown on Figure 12-5.

RESULTS

The operation of Winnibigoshish and Leech to improve walleye spawning and wild rice growing conditions, respectively, is only partially successful over the 47-year simulation period. During the summer period (May-September) 12 of 20 of the daily flood simulations exceed the target index Level 4 and in 19 of the 47 years, this level is exceeded at Winnibigoshish. In addition, in 13 years of simulation the summer reservoir level drops below the starting spawning season stage of 8.5 feet. These fluctuations in reservoir level during the 47-year simulation period may cause adverse affects on spawning walleye.

Leech Reservoir is similarly affected by extreme high and low stage years. Of the 20 daily flow simulations, 12 exceed the specified Level 4 during the period of 15 May to 10 September. For the entire 47-year period, there are 16 years in which the target level is exceeded and 12 years when the reservoir will not reach the minimum 1 April elevation of 1293.7 feet. During these periods, the conservation plan criteria for Leech will be violated and opportunities to increase wild rice production reduced.

Hydraulic Results

A summary of annual maximum and minimum elevations at reservoirs, annual maximum flow at Aitkin, and annual minimum flow at Anoka is provided in Appendix L tables together with plots of reservoir elevation versus time for the six reservoirs and streamflow at Aitkin and Anoka.

Frequency Results

Frequency relationships based on 47 years of simulated record are provided in Figures 12-7 through 12-14 for high and low stage at reservoirs, high flow at Aitkin, and low flow at Anoka. Note that in Figure 12-8 the Plan 9 low stage frequency curve is higher than the Plan 1 curve for non-exceedance frequencies between 50 and 0.2 percent. This is a result of the Leech Reservoir conservation operation plan based on the index levels shown in Figure 12-6. For Plan 9 index levels 2, 3, and 4 are all equal during the summer months. This operation minimizes permissible maximum fluctuations in Leech's stage level for the growing of wild rice, as noted above. Reservoir low stage levels stay higher as a consequence and this results in a higher low stage curve for Plan 9.

Economic Results

Table 12-2 summarizes economic computations and compares this information to Plan 1, Present Operating Plan. The results do not include the economic benefits gained by increasing walleye and wild rice production. However, the change in operation of Winnibigoshish and Leech (and their effect on Pokegama) changes the average annual damages expected for these three reservoirs. Low stage AAD for Winnibigoshish is slightly greater (11 percent) for Plan 9 than Plan 1 and is a result of the conservation policy to improve spawning. Conversely, the AAD for Leech is decreased by a total of 38 percent (compared to Plan 1) for the combined low and high stage damages because of the revised operation policy to keep the low stage reservoir level higher and to lower index level 4 to the zero damages point on the elevation-damage curve (Figure 3-15) to improve wild rice production. Pokegama's AAD rises slightly (8 percent) as a result of the conservation plans in effect at the two upstream reservoirs. Their attempts to minimize water surface level fluctuations increases downstream flows during high flow periods (and results in greater AAD at Aitkin) and decreases releases during low flow periods. Overall, the AAD for the six reservoirs decreases from $329.9K (Plan 1) to $292.8K (Plan 9). This decrease more than compensates for the increase of AAD at Aitkin from $278.6K (Plan 1) to $283.1K (Plan 9). The net result is a decrease in total AAD of 4 percent compared to Plan 1.

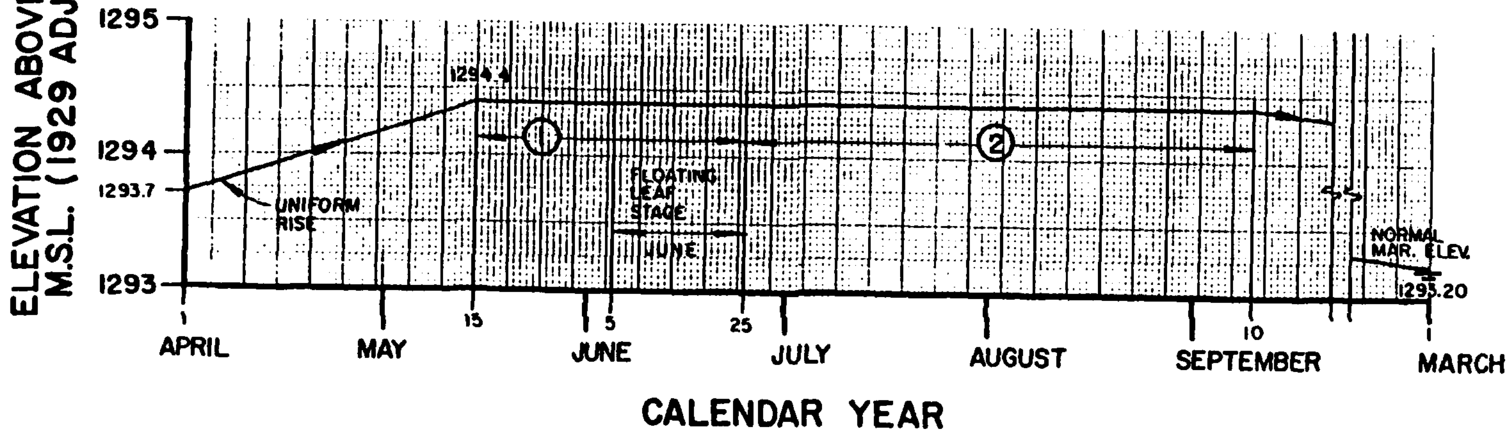
The average annual cost (AAC) of not supplying a minimum of 1600 cfs at Anoka was also calculated for Plan 9, although it was not the explicit purpose of Plan 9 to meet this requirement. However, by calculating the AAC it was then possible to compare Plan 9's average annual net benefit (or cost) relative to Plan 1. The AAC for Plan is $2962.5K compared to $3189.9K for Plan 1. The relative net benefit of Plan 9 at Anoka is $227.4K.

TABLE 12-2

ECONOMIC RESULTS
($1,000)

AVERAGE ANNUAL DAMAGE	PLAN 9	PLAN 1
Winnibigoshish		
High Stage	4.0	4.0
Low Stage	10.8	9.7
Total	14.8	13.7
Leech		
High Stage	7.6	11.0
Low Stage	43.4	71.3
Total	51.0	82.3
Pokegama		
High Stage	25.4	25.0
Low Stage	4.5	2.8
Total	29.9	27.8
Sandy		
High Stage	29.4	29.4
Low Stage	2.1	2.1
Total	31.5	31.5
Pine		
High Stage	16.6	16.6
Low Stage	6.3	6.3
Total	22.9	22.9
Gull		
High Stage	127.5	127.5
Low Stage	15.2	15.2
Total	142.7	142.7
Aitkin		
High Flow	283.1	278.6
TOTAL AAD	575.9	599.5
AVERAGE ANNUAL COST - LOW FLOW SHORTAGE (Below 1,600 cfs)		
Anoka		
Low Flow	2962.5	3,189.9

CONSERVATION PLAN - LEECH LAKE



NOTES

① ALLOW MAX. RISE OF 2" IN 48 HOURS BUT THEN STABILIZE AND BRING BACK DOWN, DURING THIS PERIOD.

② CAN WITHSTAND UP TO 6" RISE IN 48 HOURS DURING THIS PERIOD.

2500 CFS COMBINED MAXIMUM OUTFLOW FROM WINNIBIGOSHISH AND LEECH WOULD STILL BE IN EFFECT.

FIGURE 12-1

LEECH RESERVOIR MAXIMUM & MINIMUM NET RESERVOIR INFLOW
CONSERVATION PLAN REQUIREMENTS WITH OUTLET CAPACITY LIMITATIONS

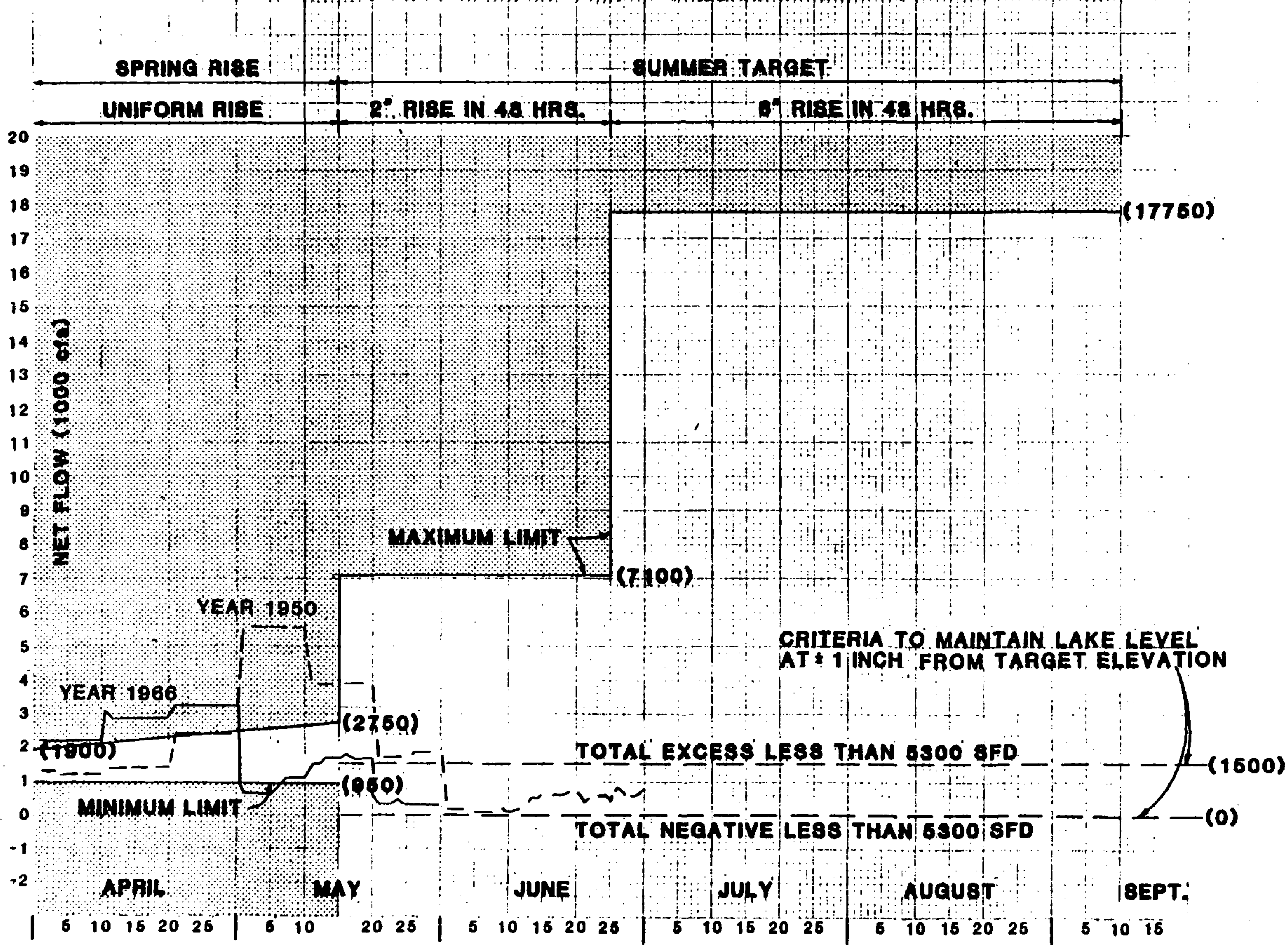


FIGURE 12-2

LEECH RESERVOIR MAXIMUM & MINIMUM NET RESERVOIR INFLOW
CONSERVATION PLAN REQUIREMENTS WITH OUTLET CAPACITY LIMITATIONS

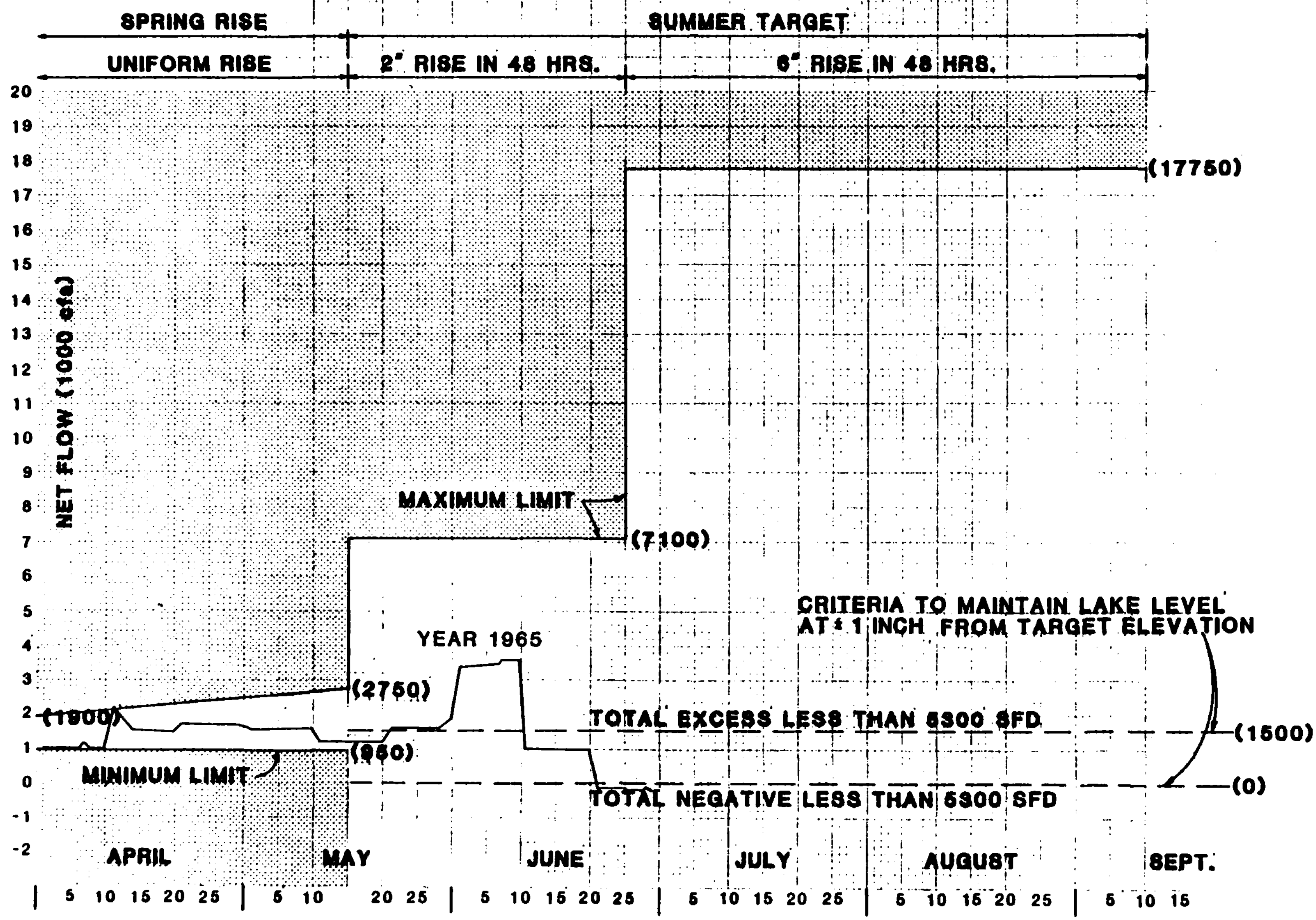
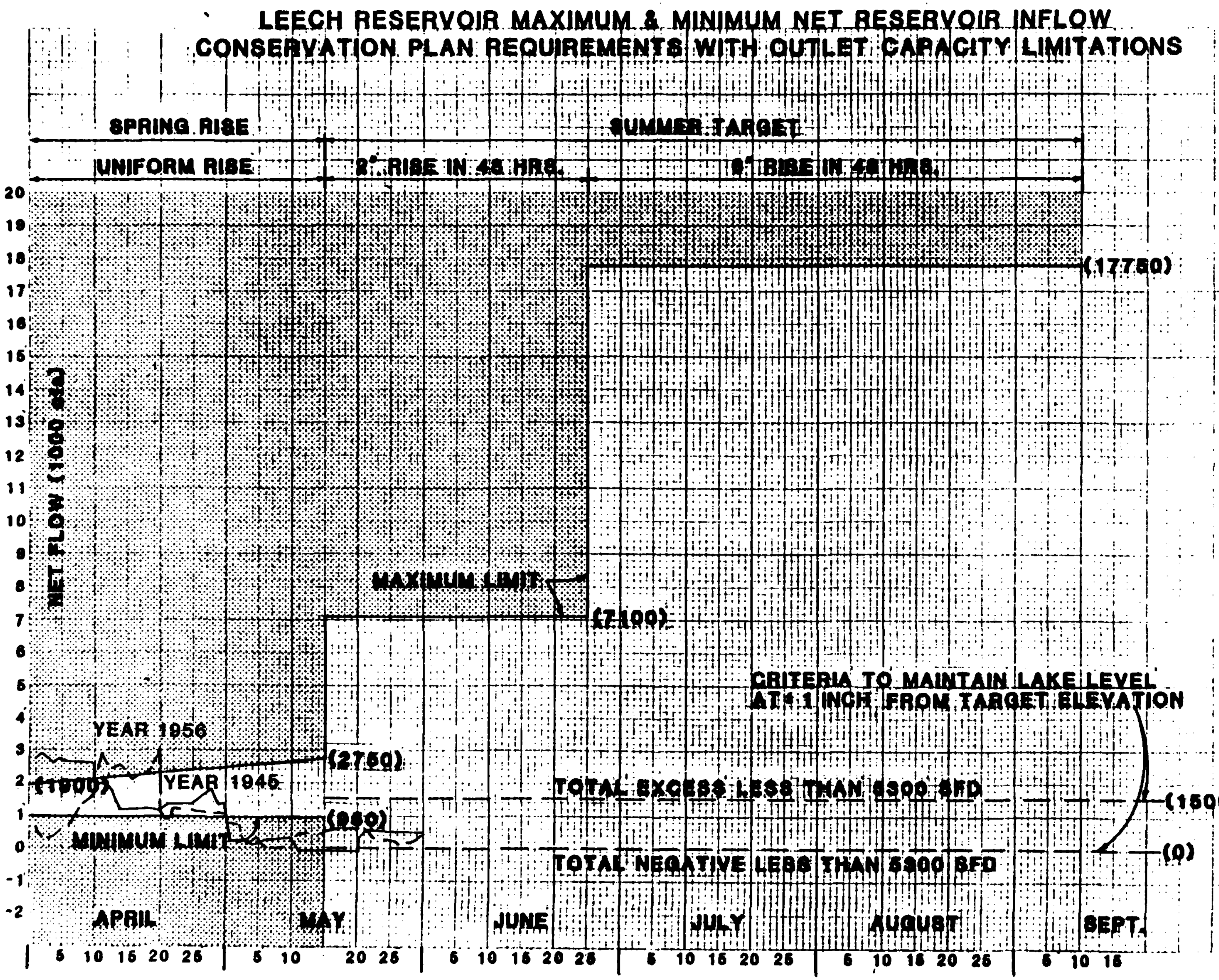
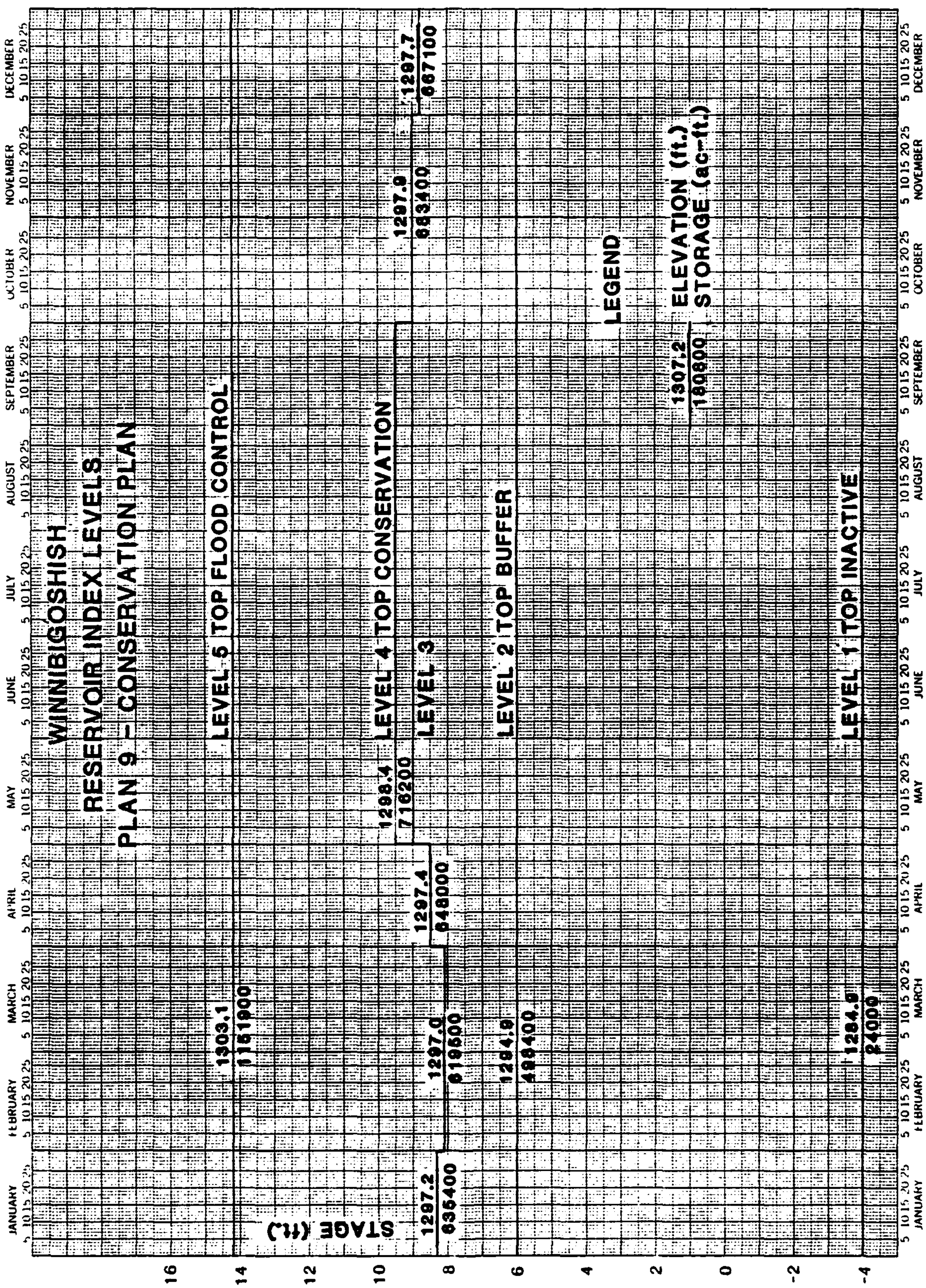


FIGURE 12-3



LEECH RESERVOIR MAXIMUM & MINIMUM NET RESERVOIR INFLOW
CONSERVATION PLAN REQUIREMENTS WITH OUTLET CAPACITY LIMITATIONS
SPRING RISE
SUMMER TARGET
UNIFORM RISE
2" RISE IN 48 HRS.
6" RISE IN 48 HRS.
NET FLOW (1000 cfs)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
(17750)
MAXIMUM LIMIT
(7100)
CRITERIA TO MAINTAIN LAKE LEVEL
AT ± 1 INCH FROM TARGET ELEVATION
YEAR 1956
(2750)
(1900)
YEAR 1945
TOTAL EXCESS LESS THAN 5300 SFD
(1500)
(950)
MINIMUM LIMIT
(0)
TOTAL NEGATIVE LESS THAN 5300 SFD
APRIL
MAY
JUNE
JULY
AUGUST
SEPT.
5 10 15 20 25
5 10 20 25
5 10 15 20 25
5 10 15 20 25
5 10 15 20 25
5 10 15

FIGURE 12-4



WINNIBIGOSHISH
RESERVOIR INDEX LEVELS
PLAN 9 - CONSERVATION PLAN
LEVEL 5 TOP FLOOD CONTROL
LEVEL 4 TOP CONSERVATION
LEVEL 3
LEVEL 2 TOP BUFFER
LEVEL 1 TOP INACTIVE
LEGEND
ELEVATION (ft.)
STORAGE (ac-ft.)
1307.2
180800
1303.1
1151900
1297.2
635400
1297.0
619600
1294.9
498400
1284.9
24000
1297.4
648000
1298.4
716200
1297.9
683400
1297.7
667100
STAGE (ft.)
16
14
12
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 12-5

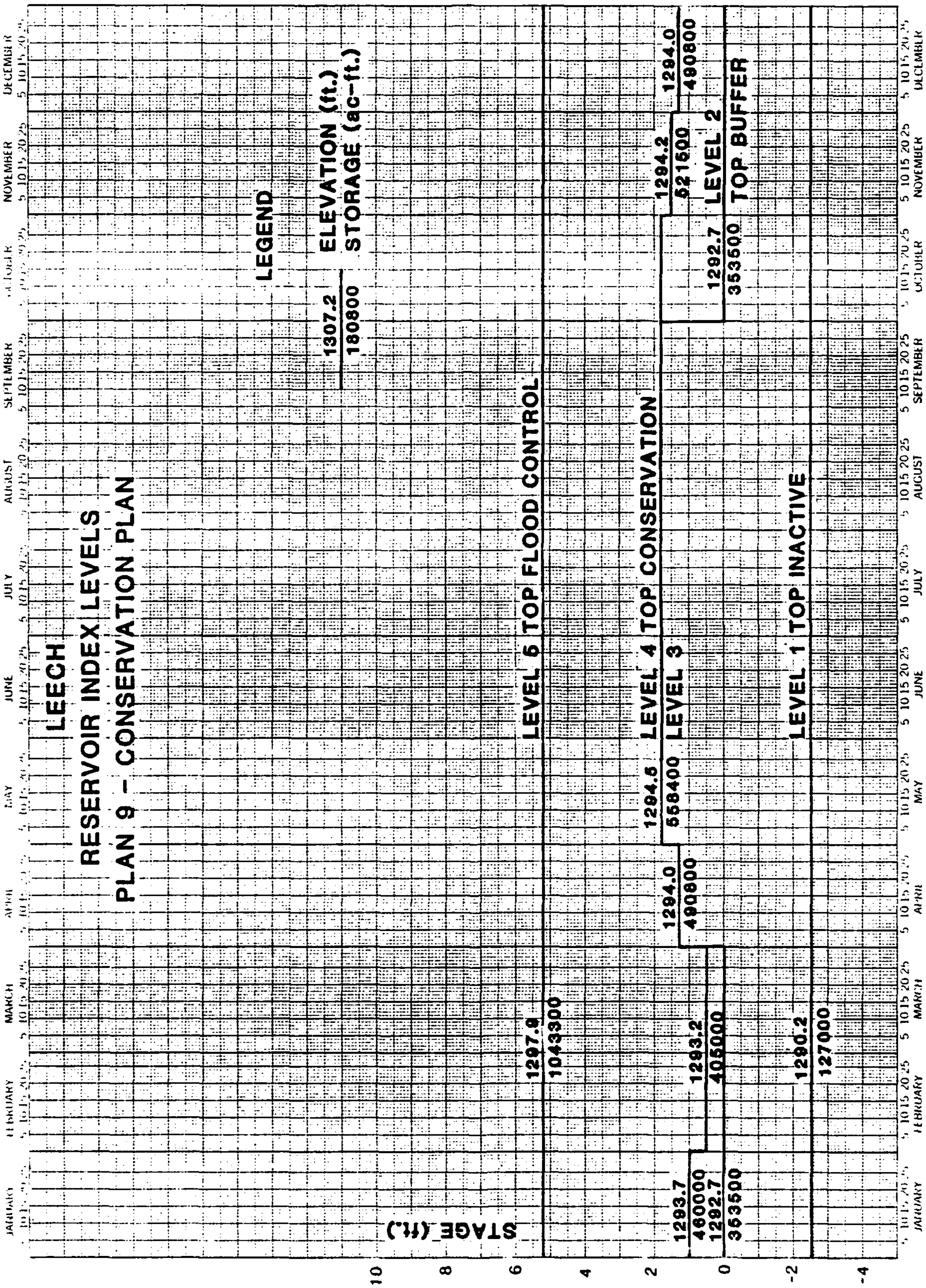

LEECH
RESERVOIR INDEX LEVELS
PLAN 9 - CONSERVATION PLAN
LEGEND
1307.2
180800
ELEVATION (ft.)
STORAGE (ac-ft.)
LEVEL 6 TOP FLOOD CONTROL
1297.9
1043300
LEVEL 4 TOP CONSERVATION
LEVEL 3
1294.5
558400
1294.0
490800
1293.7
460000
1292.7
353500
1293.2
405000
1292.7
353500
1294.2
521600
LEVEL 2
TOP BUFFER
1294.0
490800
LEVEL 1 TOP INACTIVE
1290.2
127000
STAGE (ft.)
10
8
6
4
2
0
-2
-4
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

FIGURE 12-6

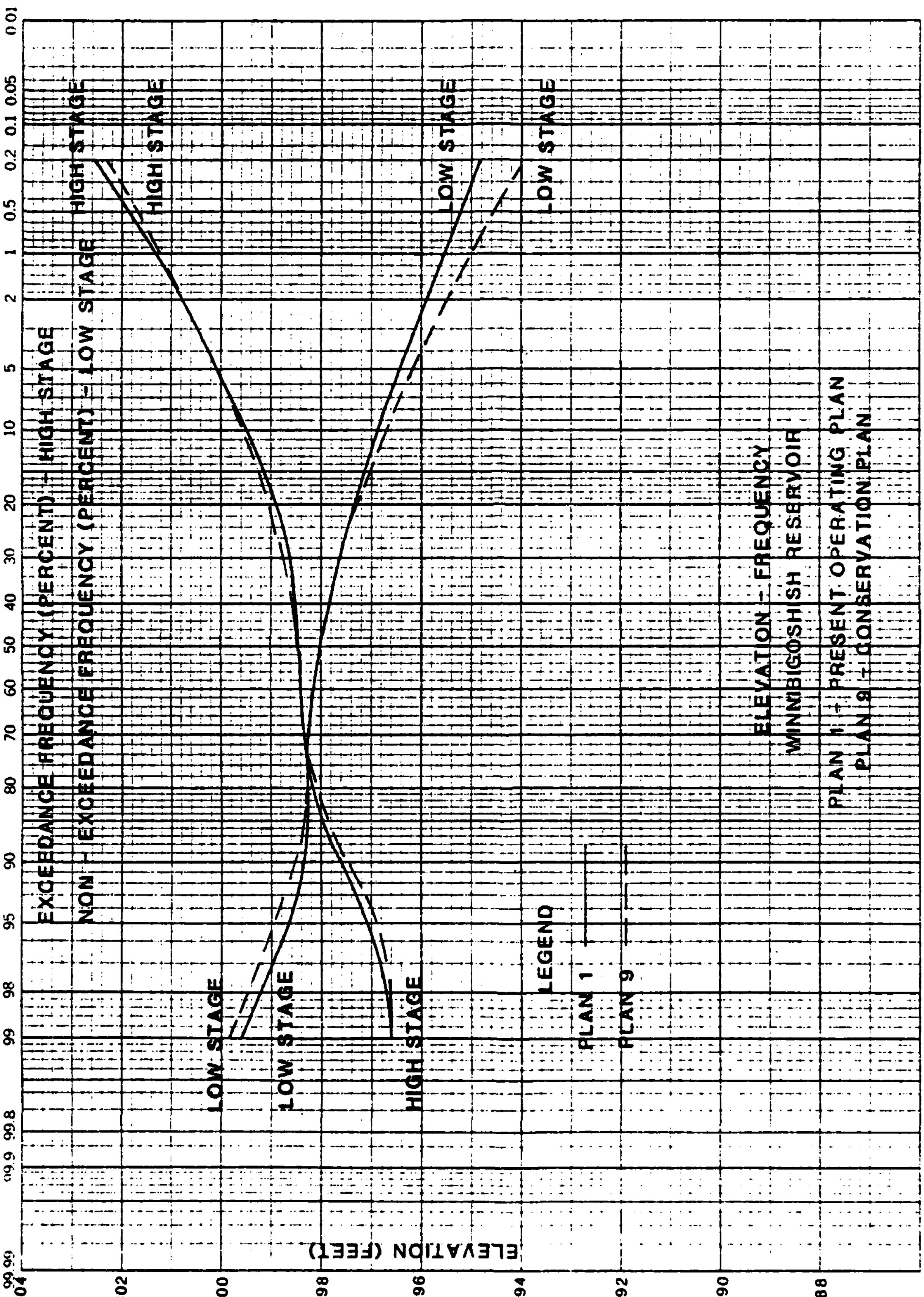

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
ELEVATION - FREQUENCY
WINNIBIGOSHISH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN
LEGEND
PLAN 1
PLAN 9
ELEVATION (FEET)
1304
1302
1300
1298
1296
1294
1292
1290
1288

FIGURE 12-7

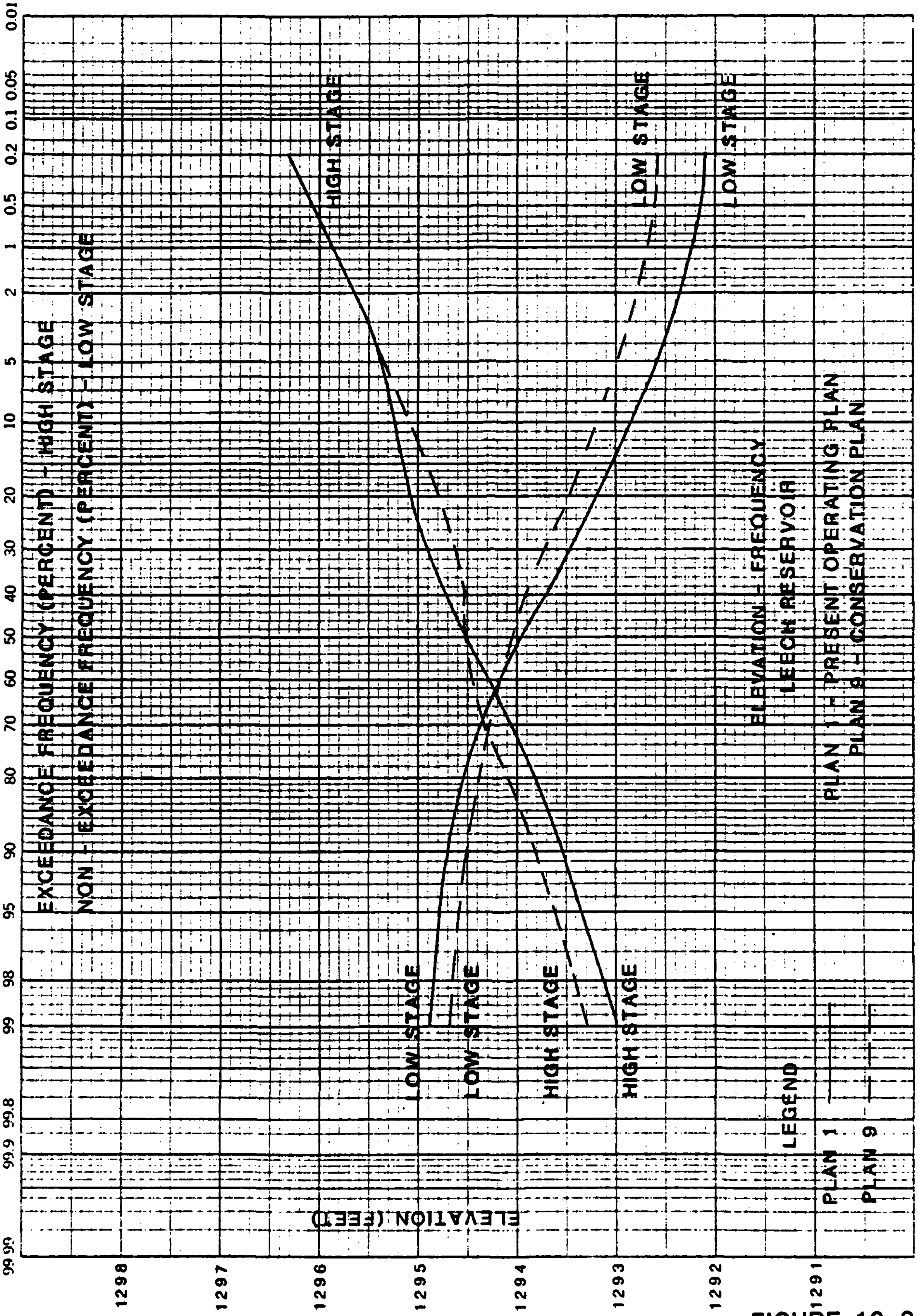

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
ELEVATION (FEET)
ELEVATION - FREQUENCY
LEECH RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN
LEGEND
PLAN 1
PLAN 9
HIGH STAGE
LOW STAGE
LOW STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
1298
1297
1296
1295
1294
1293
1292
1291

FIGURE 12-8

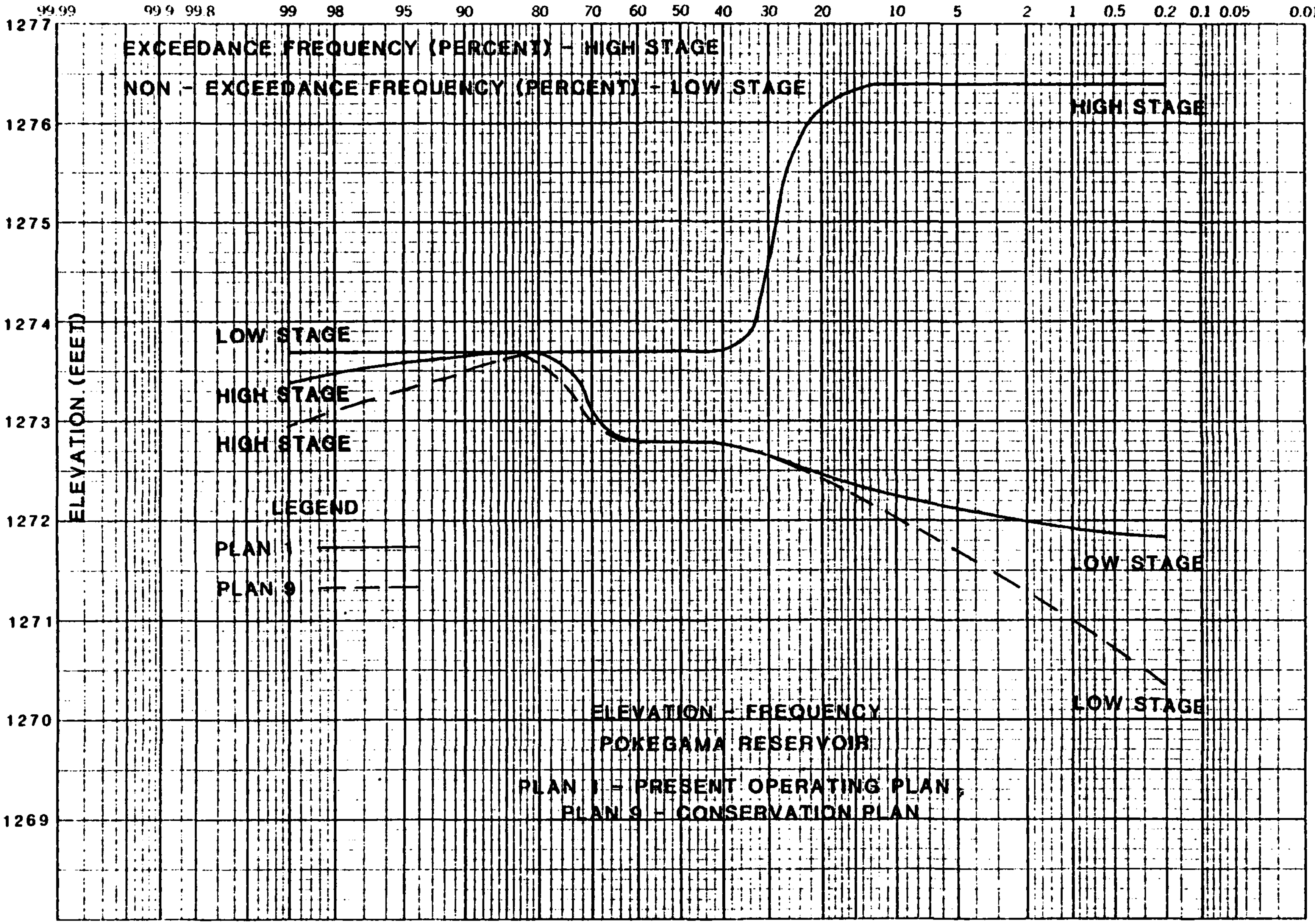

99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
1277
1276
1275
1274
1273
1272
1271
1270
1269
ELEVATION (FEET)
EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
LOW STAGE
HIGH STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 9
LOW STAGE
LOW STAGE
ELEVATION - FREQUENCY
POKEGAMA RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN,
PLAN 9 - CONSERVATION PLAN

FIGURE 12-9

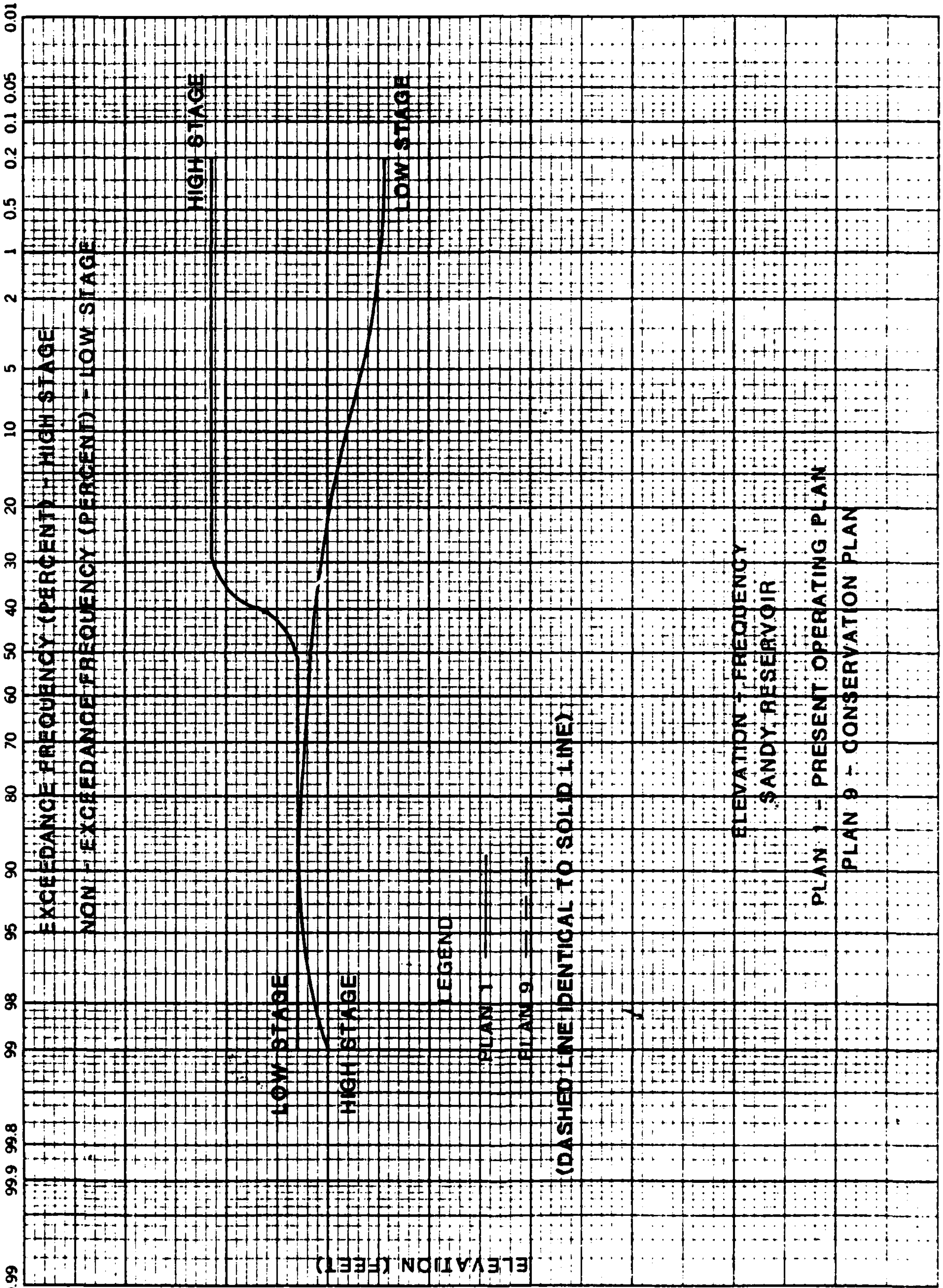

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
PLAN 9
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
SANDY RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN
ELEVATION (FEET)
1220
1218
1216
1214
1212
1210
1208
1206

FIGURE 12-10

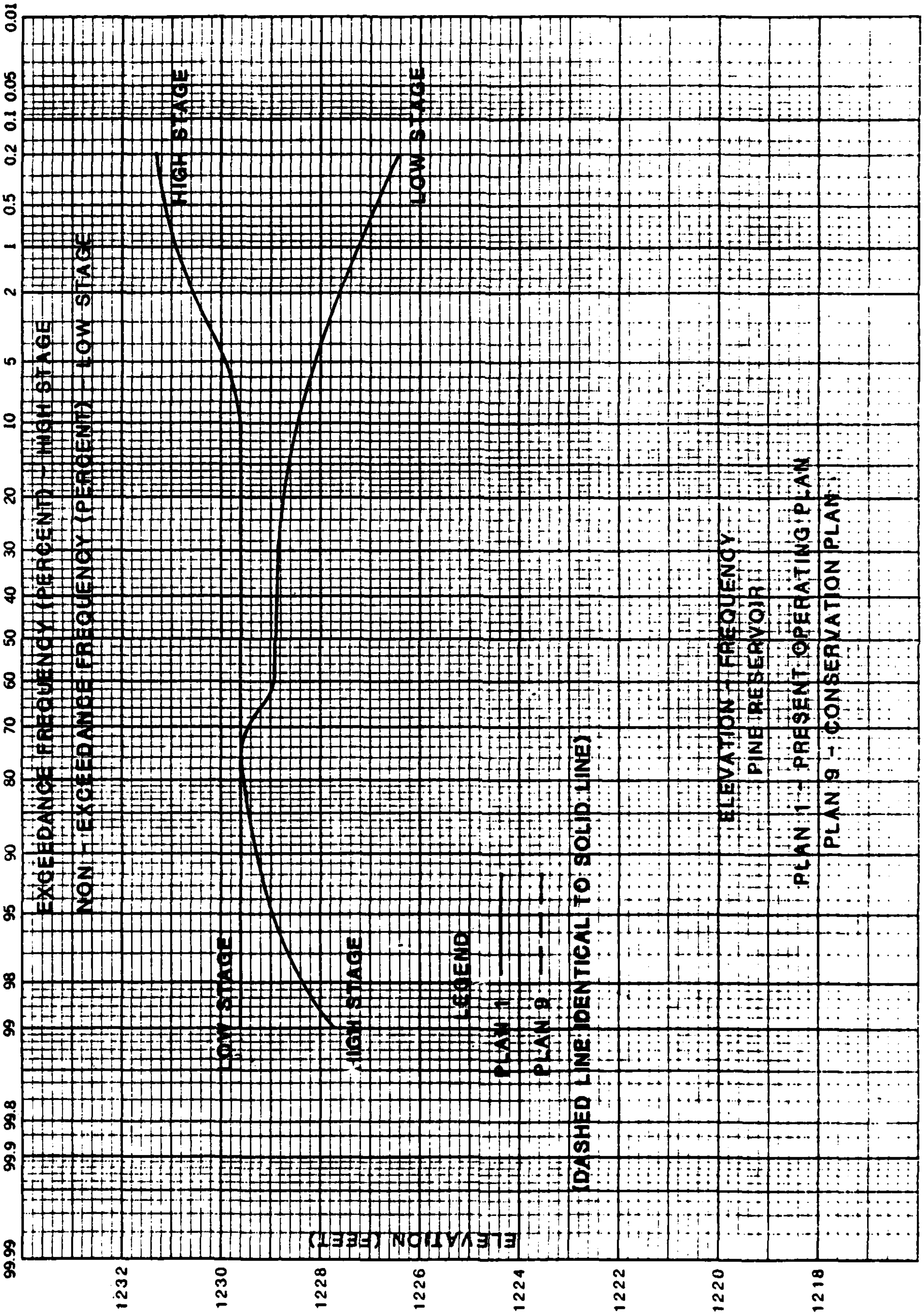

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
ELEVATION (FEET)
1232
1230
1228
1226
1224
1222
1220
1218
HIGH STAGE
LOW STAGE
LOW STAGE
IGH STAGE
LEGEND
PLAN 1
PLAN 9
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
PINE RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN

FIGURE 12-11

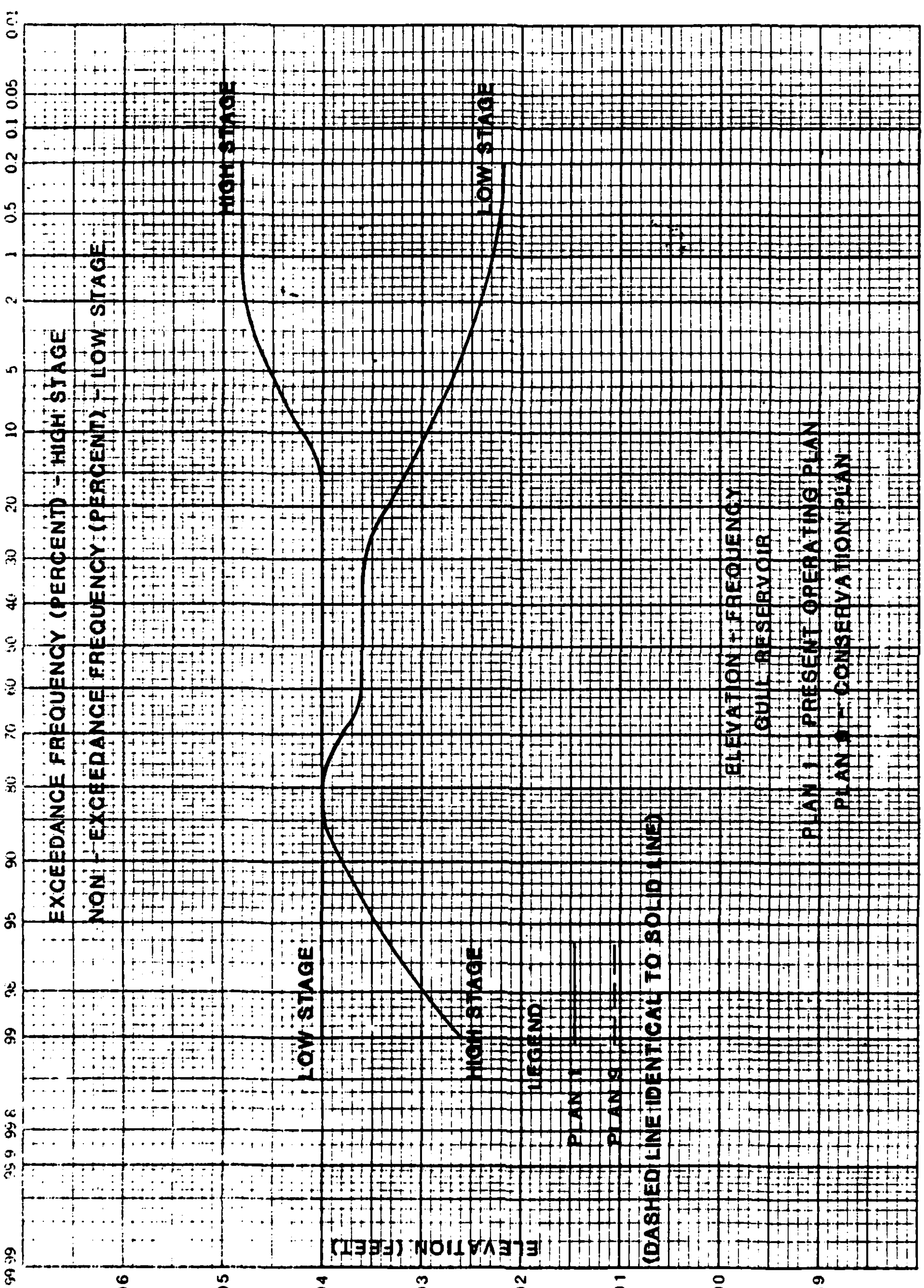

EXCEEDANCE FREQUENCY (PERCENT) - HIGH STAGE
NON - EXCEEDANCE FREQUENCY (PERCENT) - LOW STAGE
HIGH STAGE
LOW STAGE
LOW STAGE
HIGH STAGE
LEGEND
PLAN 1
(DASHED LINE IDENTICAL TO SOLID LINE)
ELEVATION - FREQUENCY
GULL RESERVOIR
PLAN 1 - PRESENT OPERATING PLAN
CONSERVATION PLAN
ELEVATION (FEET)
1196
1195
1194
1193
1192
1191
1190
1189

FIGURE 12-12

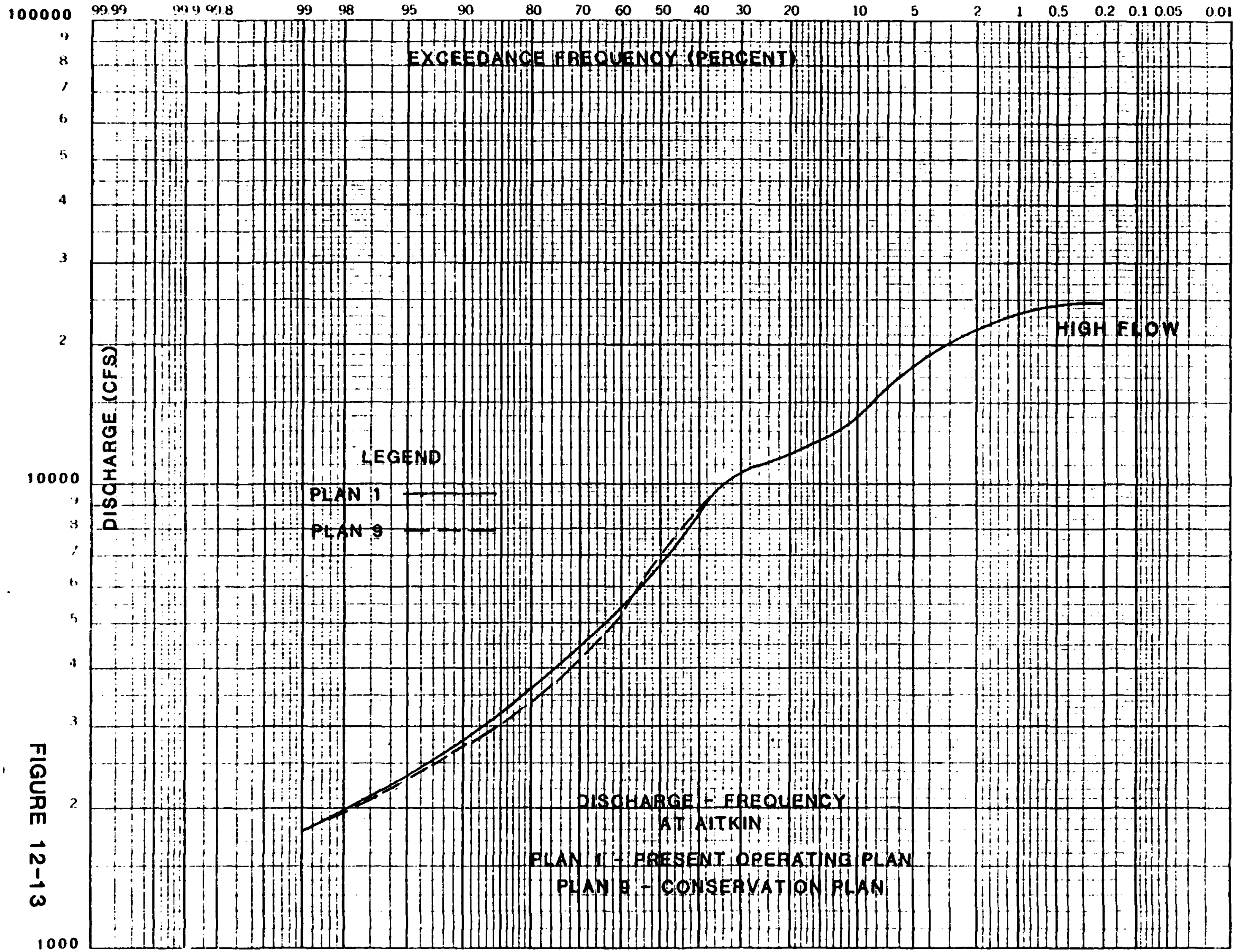

EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
HIGH FLOW
LEGEND
PLAN 1
PLAN 9
DISCHARGE - FREQUENCY
AT AITKIN
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN

FIGURE 12-13

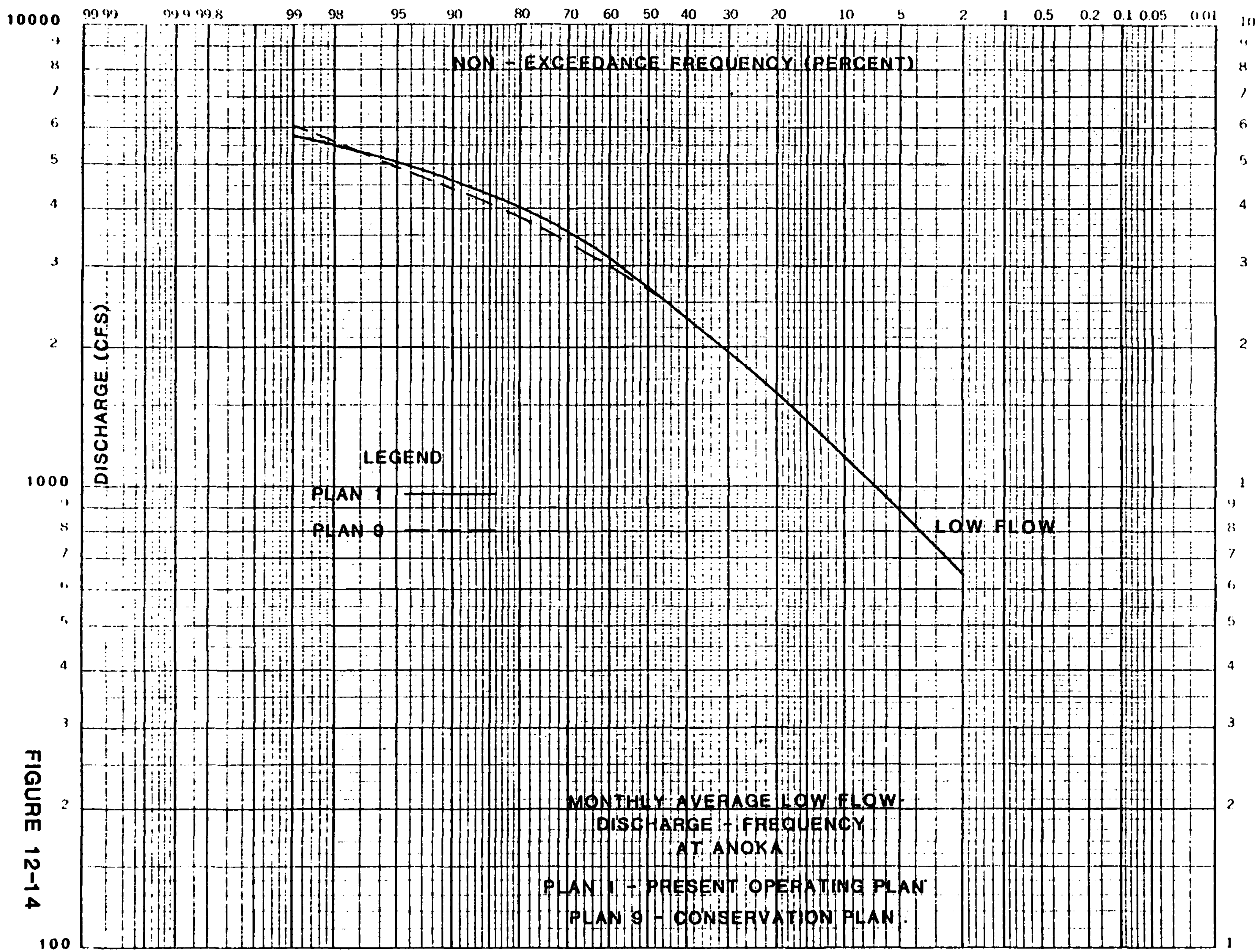

NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)
LEGEND
PLAN 1
PLAN 9
LOW FLOW
MONTHLY AVERAGE LOW FLOW
DISCHARGE - FREQUENCY
AT ANOKA
PLAN 1 - PRESENT OPERATING PLAN
PLAN 9 - CONSERVATION PLAN

FIGURE 12-14

SECTION 13

PLAN 10 - SANDY LAKE PLAN

OBJECTIVE

The objective of this plan is to investigate the effect of operating Sandy Lake Dam, during high flow periods in April and May, with open gates in order to utilize the natural tailwater effect of Mississippi River high stage to regulate the rise of Sandy Reservoir stage to the summer target level.

DISCUSSION

This plan would allow a Sandy Lake drawdown to normal spring level and then gradually open Sandy Lake control gates to maintain the spring drawdown level. As the Mississippi River rises and Sandy Lake and the Mississippi River are equalized, the control gates at Sandy Lake are left wide open to allow the Mississippi River and Sandy Lake to rise together.

Inherent with this plan is the need to compute reservoir releases based upon tailwater conditions, and in this case, upon tailwater conditions at a downstream control point (Libby). In addition, under certain extreme flow conditions at Libby, it is possible to have a reverse flow condition at the reservoir outlet with gates open. HEC-5 does not have either of these capabilities.

Since this plan would only be used under certain hydrologic conditions which would not occur every year, it is possible to perform a hand routing procedure at Sandy Lake Dam based upon the rating curve at Libby; slope rating curve at Sandy River, Sandy Lake Dam and Reservoir; and the discharge hydrographs at Libby (Mississippi River) and inflow to Sandy Reservoir. Even with this procedure, it is still difficult to compare Plan 10 results with Sandy Reservoir results under Plan 1, Present Operating Plan, since HEC-5 uses constant reservoir index level targets for a monthly period. In order to evaluate this plan, daily routing must be performed.

Due to the above limitations, a complete simulation of Plan 10 was not performed; however, the hand routing procedure is included and gives some insight into the impact of Plan 10 operation. Details of this procedure are included in Appendix M.

SECTION 14
SENSITIVITY ANALYSIS, RESERVOIR ELEVATION-AREA-CAPACITY CURVES

Objective

This analysis demonstrates the change in objective function results which would be caused by errors in the reservoir elevation-area-capacity relationships. The effects of errors in the specified relationships for the three upstream reservoirs (Winnibigoshish, Leech, and Pokegama) on regulated low flows at Anoka are simulated and discussed as the basis for this demonstration.

Discussion

The reliability of computer simulation results is highly dependent on the accuracy of the data used as input to the computer model. One of thge most important types of data used in a simulation study involving reservoirs is the definition of available storage based on elevation-area-capacity relationships. Storage volume is important to study results and subsequent reservoir operation for two major reasons. First, it provides an attenuation effect on major flood flows by temporarily storing inflows and releasing outflows at a reduced level over a longer period of time. Second, the reservoir storage provides a conservation capability by storing higher flows for release in low flow periods.

Elevation-area-capacity relationships for the reservoirs in the Mississippi River Headwaters area are based on survey data collected in 1925 and/or 1931, with some revisions in 1941. The St. Paul District has expressed concern regarding the accuracy of this data particularly in the lower elevation regions of each lake. Since potential errors introduced by inaccurate survey data have a more pronounced effect on incremental storage at lower elevation levels than at upper lake levels, it is likely that such errors exert a greater impact on low flow, conservation functions than on high flow, flood control functions. Consequently, the following analysis of potential changes to objective functions focuses solely on conservation practices. In particular, the effects of reduced storage in the upper three reservoirs (Winnibigoshish, Leech, and Pokegama) on regulated low flows at Anoka are examined.

Earlier analysis of simulation results for Plan 2 (Section 5) indicated that the study reservoirs could be operated such that a minimum flow requirement of 1,600 cfs was accomplished at Anoka for the entire 47-year period of simulation. (It should be noted that this result and the following sensitivity analysis were conducted prior to the reintroduction of the HEC-5 error which affects the Plans 2, 5, and 6 results.) While errors in survey data which result in underestimation of reservoir storage would not adversely affect on fulfillment of required flows at Anoka for the simulation period, overestimation of storage volume could result in inappropriate operation of reservoirs with premature release of waters which are needed later in the year to meet minimum flow requirements.

In order to investigate the potential effects of inaccurate survey data on conservation practices, two sensitivity analysis runs were performed by adjusting the elevation-area-capacity data for Plan 2. In the first computer run (Plan 2S1), it was assumed that all elevation data for each of the upper three reservoirs overestimated the depth of water uniformly by one foot. The second sensitivity run (Plan 2S2) assumed an overestimation of two feet. Figures 14-1 and 14-2 are provided as aids in visualizing the assumptions made in these two sensitivity runs. Figure 14-1 illustrates an idealized cross-section for Winnibigoshish Lake based on depth and volume data and the assumption of a circular shape at every level of the lake. The effects on this idealized cross-section resulting from an overestimation of water depth at all points by 1 foot (Plan 2S1) and by 2 feet (Plan 2S2) are indicated on the figure. Average cross-sections for Leech and Pokegama Lakes were modified in a similar manner to represent parallel overestimations of reservoir depth.

Figure 14-2 shows the modifications to the existing stage-storage curve for Winnibigoshish Lake which are necessary to represent Plans 2S1 and 2S2. The figure illustrates that the relative impact of errors in survey data on storage volume is greater at the lower levels of the reservoir. For example, a uniform 1 foot overestimation of reservoir depth results in a 31 percent reduction in storage at an elevation of 1288 feet, while only a 9 percent reduction in storage results at an elevation of 1300 feet.

Necessary adjustments were made to RE and RL cards in the HEC-5 input sequence to modify the stage-storage relationship and the reservoir index levels in each of the upper three reservoirs. Resulting low-flow data (monthly minimum flows) at Anoka were then simulated for the period 1930-1976 and analyzed for the two sensitivity runs.

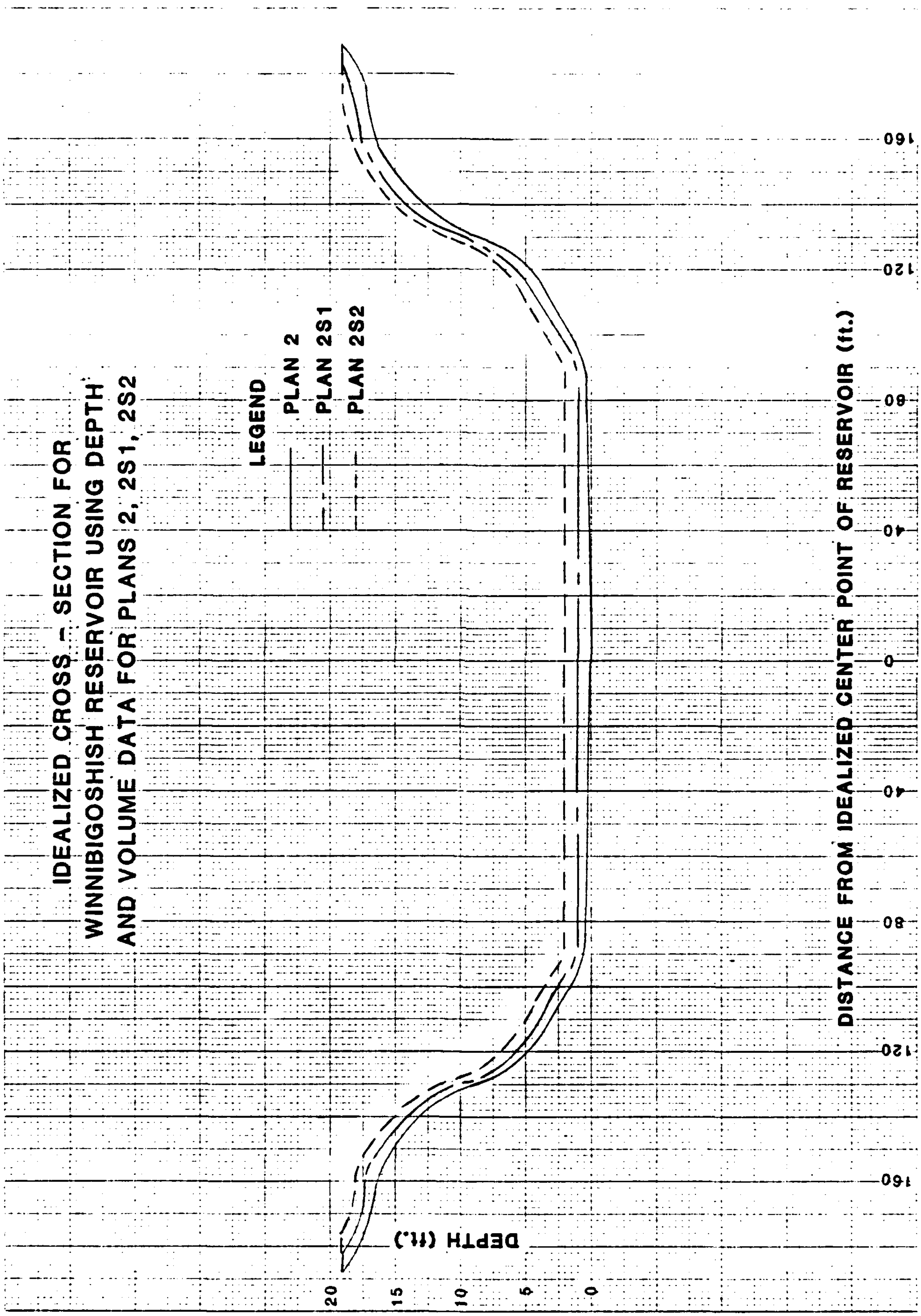
RESULTS

Simulation results for Plan 2S1 indicated that the minimum flow requirement of 1,600 cfs at Anoka would be accomplished even if reservoir depth in each of the three upper reservoirs was overestimated by 1 foot. In fact, overestimation of depth by 2 feet (Plan 2S2) only violated the minimum flow requirement during one month of the 47-year simulation period. Simulated minimum flow at Anoka for January 1935 dipped below the 1,600 cfs level to 1,365 cfs. To illustrate the downstream effects of overestimating reservoir depth, and hence, storage volume, in the three reservoirs, Figure 14-3 provides plots of yearly minimum flow values at Anoka during the simulation period for Plans 2 and 2S2. Several periods of the simulation period are of interest. During the drought period of 1930-1938 storage in the reservoirs is reduced to a point where failure to meet the 1,600 cfs requirement at Anoka is a constant concern, and at one point the requirements simply cannot be met if reservoir depth is indeed overestimated by 2 feet (Plan 2S2). Other differences in minimum yearly flow between the two plans occur during the periods 1942-1946, 1950-1954, 1968, and 1972. For these years, low flow occurs during winter months rather than summer months. Under this condition, there is less incremental storage between equal reservoir elevations in Plan 2S2 than Plan 2. As a result, lower releases are made in Plan 2S2 than Plan 2 in order to bring the reservoir down to a lower elevation as prescribed in each plan.

The most important point illustrated by Figure 14-3 is that even with a 2-foot overestimation of reservoir depth for all three of the upper reservoirs, the 1,600 cfs flow requirement at Anoka is only violated once.

Minimum yearly flow at Anoka is presented in the form of frequency curves in Figure 14-4. Note that overestimation of reservoir depths by 1 foot (Plan 2S1) has no visible effect on the original frequency curve for

Plan 2, and that the only significant difference in the frequency curve for Plan 2S2 lies in the area of infrequent events. This is another indication that overestimation of reservoir depths does not significantly affect the ability of the Mississippi River Headwaters reservoirs to satisfy the flow requirements at Anoka.



IDEALIZED CROSS - SECTION FOR
WINNIBIGOSHISH RESERVOIR USING DEPTH
AND VOLUME DATA FOR PLANS 2, 2S1, 2S2
LEGEND
PLAN 2
PLAN 2S1
PLAN 2S2
DISTANCE FROM IDEALIZED CENTER POINT OF RESERVOIR (ft.)
160
120
80
40
0
40
80
120
160
DEPTH (ft.)
20
15
10
5
0

FIGURE 14-1

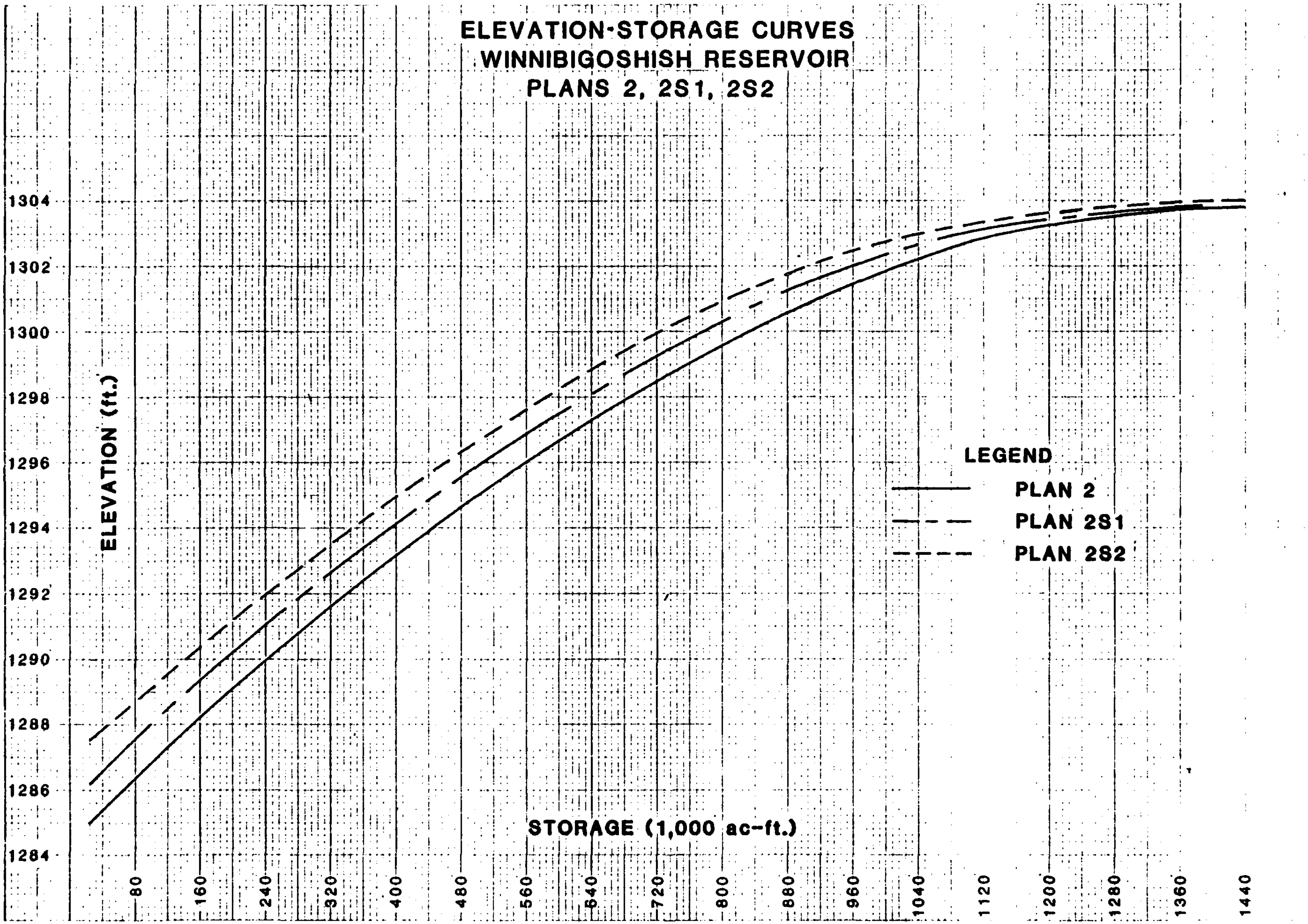


FIGURE 14-2

20 Squares to the Inch

MINIMUM FLOW AT ANOKA FOR PLANS 2 & 2S2, 1930-1976

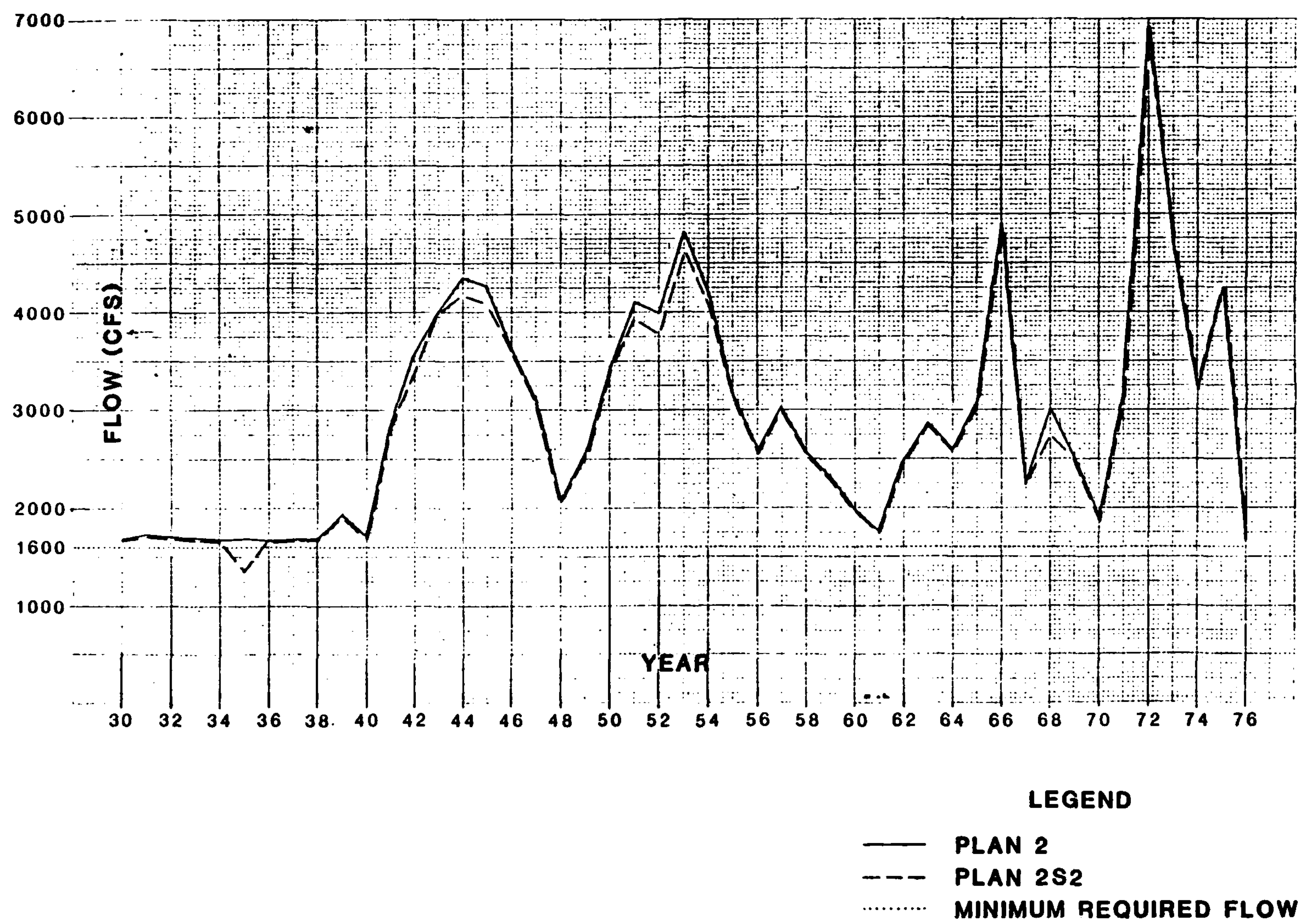
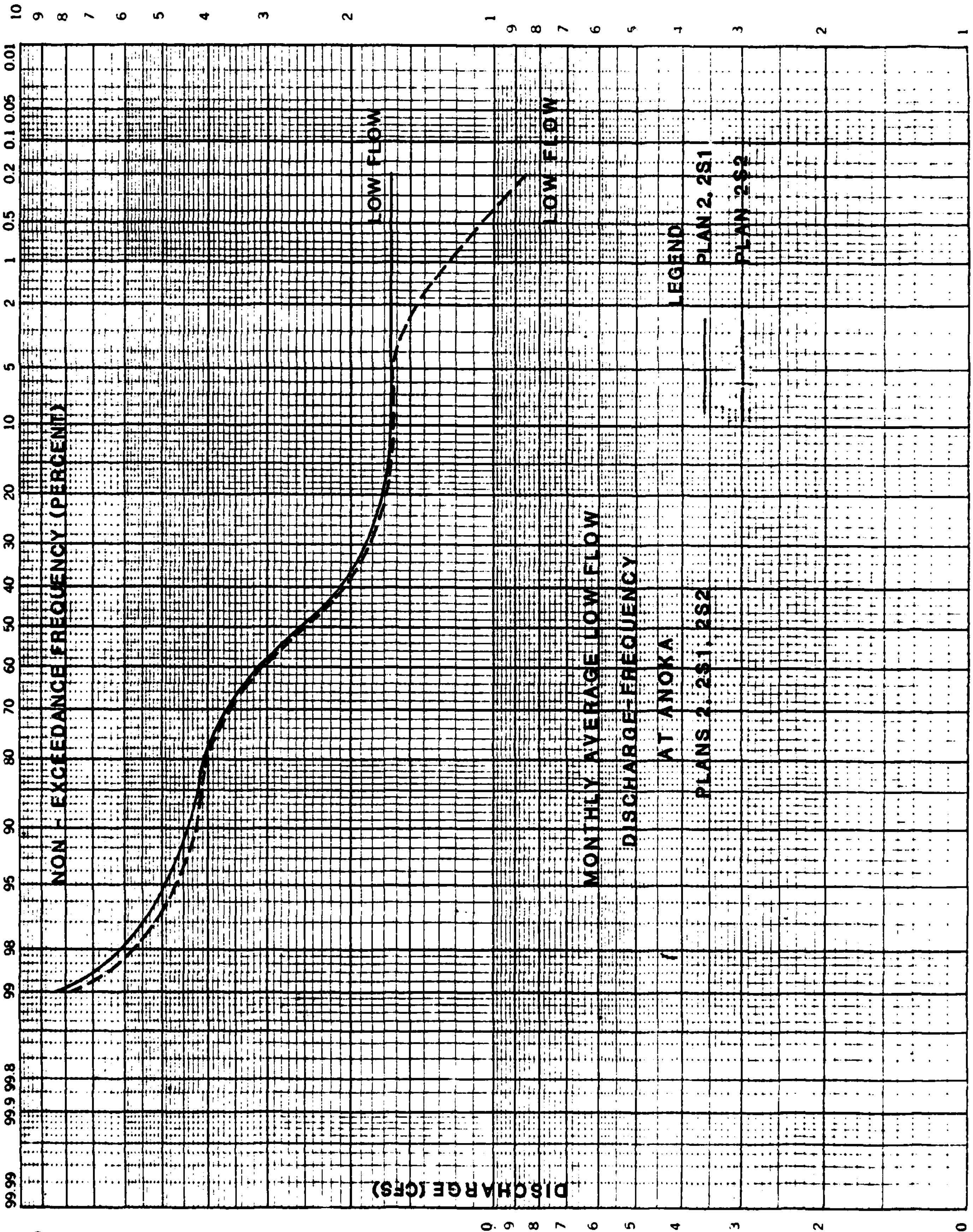


FIGURE 14-3



MONTHLY AVERAGE LOW FLOW
DISCHARGE-FREQUENCY
AT ANOKA
PLANS 2, 2S1, 2S2
LEGEND
PLAN 2, 2S1
PLAN 2S2
LOW FLOW
LOW FLOW
NON - EXCEEDANCE FREQUENCY (PERCENT)
DISCHARGE (CFS)

FIGURE 14-4

REFERENCES

1. Bowers, C. Edward; Nelson, Nels P.; Gutschick, Carlton K.; Schevenius, Wesley C.; "The Effects of Different Operating Plans for the Six Mississippi River Headwaters Dams; St. Anthony Falls Hydraulics Laboratory, University of Minnesota, Minneapolis, Minnesota; August 1979.

2. U.S. Army Corps of Engineers, St. Paul District; "Stage 2 Summary Report, Mississippi River Headwaters Lakes Study"; St. Paul, Minnesota; September 1979.

3. U.S. Army Corps of Engineers, Hydrologic Engineering Center; "HEC-5 Simulation of Flood Control and Conservation Systems Users Manual"; Davis, California; June 1979 revised December 1979.

4. U.S. Army Corps of Engineers, Hydrologic Engineering Center; Expected Annual Flood Damage Computation Users Manual; Davis, California; June 1977 revised August 1979.

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